

FORMALDEHYDE DENSITOMETRY OF GALACTIC STAR-FORMING REGIONS USING THE H₂CO 3₁₂-3₁₃ AND 4₁₃-4₁₄ TRANSITIONS

PATRICK I. MCCAULEY, JEFFREY G. MANGUM, AND ALWYN WOOTTEN
 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903
Draft version August 19, 2011

ABSTRACT

We present Green Bank Telescope (GBT) observations of the 3₁₂-3₁₃ (29 GHz) and 4₁₃-4₁₄ (48 GHz) transitions of the H₂CO molecule toward a sample of 23 well-studied star-forming regions. Analysis of the relative intensities of these transitions can be used to reliably *measure* the densities of molecular cores. Adopting kinetic temperatures from the literature, we have employed a Large Velocity Gradient (LVG) model to derive the average hydrogen number density $[n(\text{H}_2)]$ within a 16'' beam toward each source. Densities in the range of $10^{5.5}$ – $10^{6.5}$ cm⁻³ and ortho-formaldehyde column densities per unit line width between $10^{13.5}$ and $10^{14.5}$ cm⁻² (km s⁻¹)⁻¹ are found for most objects, in general agreement with existing measurements. A detailed analysis of the advantages and limitations to this densitometry technique is also presented. We find that H₂CO 3₁₂-3₁₃/4₁₃-4₁₄ densitometry proves to be best suited to objects with $T_K \gtrsim 100$ K, above which the H₂CO LVG models become relatively independent of kinetic temperature. This study represents the first detection of these H₂CO *K*-doublet transitions in all but one object in our sample. The ease with which these transitions were detected, coupled with their unique sensitivity to spatial density, make them excellent monitors of density in molecular clouds for future experiments. We also report the detection of the 9₂-8₁ A⁻ (29 GHz) transition of CH₃OH toward 6 sources.

Subject headings: ISM: clouds — ISM: molecules — stars: formation

1. INTRODUCTION

A thorough understanding of star formation is predicated on a knowledge of the physical conditions that surround the process at each of its stages. The determination of these properties has proven to be a challenging endeavour for the early phases of star formation because molecular hydrogen (H₂), the primary constituent of developing stars, cannot be measured directly. Instead, the excitation properties of trace molecules must be used to infer the conditions within the greater cloud. Thus, all measurements of density in molecular clouds are subject to the biases of the chosen tracer. Even more problematic are virial density estimates determined via inferred mass and source size due to the uncertainties inherent in both quantities. Formaldehyde (H₂CO) is uniquely sensitive to spatial density and an ideal probe of molecular cloud cores for a number of reasons that are discussed in §2.

The 1₁₀-1₁₁ (5 GHz) and 2₁₁-2₁₂ (14 GHz) *K*-doublet transitions of H₂CO have previously been used to measure density in a number of studies of galactic (e.g. Henkel et al. 1980; Dickel & Goss 1987; Turner et al. 1989; Zylka et al. 1992) and extragalactic (Mangum et al. 2008) star formation regions. Our work employs an essentially identical strategy using the 3₁₂-3₁₃ (29 GHz) and 4₁₃-4₁₄ (48 GHz) transitions, which offer a few advantages over their lower excitation counterparts. Principally, the higher frequencies translate to smaller single-dish beam sizes (GBT beam sizes of 26'' and 16'' for the $J = 3$ and $J = 4$ transitions, respectively, as opposed to 153'' and 51'' for $J = 1$ and $J = 2$ *K*-doublets). The added spatial resolution is important when considering that stars form in spatially compact regions within molecular clouds and thus large beam sizes

may serve to dilute the areas of interest. This point is compounded by the fact that the lower excitation transitions are by their nature often more sensitive to spatial densities and kinetic temperatures lower than those of interest in studies of star-forming molecular cores. The 3₁₂-3₁₃ and 4₁₃-4₁₄ transitions are therefore more efficient probes of spatial density in this context.

Few studies of the $J = 3$ and 4 *K*-doublet transitions have been made due partially to their relatively low intensities and high centimeter-wave frequencies. The $J = 3$ transition was first detected by Welch (1970) in absorption toward the radio continuum source Sgr B2. Subsequent experiments were conducted toward the brightest source in our sample, Orion-KL (Wilson et al. 1980; Myers & Buxton 1980; Bastien et al. 1985), after which exploration of this transition seemingly ends. We could find no previous measurements of the 4₁₃-4₁₄ transition, whose yet higher frequency and weaker intensity pose additional observational difficulties.

Since our ability to detect these transitions and the reliability of deriving density measurements from them was uncertain, a sample of very bright and well-studied objects were chosen (Table 1). Strong detections of both transitions proved to be fairly easy to obtain, requiring an average of 17 min of integration time, and the resulting spatial density measurements ($10^{5.5}$ – $10^{6.5}$ cm⁻³) are consistent with what is known for molecular cores. These results are encouraging for the prospect of future experiments.

Details on the utility of H₂CO as a high-density probe are given in §2. In §3 our observational and calibration procedures are presented with a brief discussion of the measurement results in §4. §5 describes the details of our analysis, including a discussion of the Large Velocity

TABLE 1
SOURCE POSITIONS

Source	α (J2000.00)	δ (J2000.00)	Distance (pc)	V_{LSR} (km s ⁻¹)
W3 IRS 4	02 ^h 25 ^m 30 ^s .92	62°06′20″.70	1,950 ¹	-35.0
W3(OH)	02 27 04.31	61 52 23.90	1,950 ¹	-50.0
L1448 IRS 3B	03 25 36.33	30 45 15.00	232 ²	8.0
NGC 1333 IRAS 4A	03 29 10.52	31 13 31.00	235 ²	6.8
NGC 1333 IRAS 4B	03 29 12.00	31 13 07.80	235 ²	6.8
L1551 IRS 5	04 31 34.07	18 08 05.10	140 ³	6.4
Orion-KL	05 35 14.46	-05 22 27.50	418 ⁴	9.0
Orion-N	05 35 14.45	-05 21 03.20	418 ⁴	9.0
Orion-S	05 35 13.55	-05 24 08.30	418 ⁴	6.5
OMC-2 IRS 4	05 35 27.32	-05 09 39.6	430 ⁵	11.0
IRAS 05338-0624	05 36 18.42	-06 22 06.20	480 ⁶	7.1
NGC 2024	05 41 44.53	-01 55 02.90	415 ⁵	11.0
NGC 2024 FIR 5	05 41 44.47	-01 55 42.50	415 ⁵	11.0
NGC 2024 FIR 6	05 41 45.16	-01 56 04.80	415 ⁵	11.0
NGC 2071 IR	05 47 04.85	00 21 43.00	390 ⁵	10.0
S255N	06 12 53.67	18 00 26.60	1,590 ⁷	8.0
G34.26+0.15	18 53 18.60	01 14 58.40	3,700 ⁸	58.7
S68N	18 29 47.91	01 16 46.50	230 ⁹	8.8
W51M	19 23 44.01	14 30 34.10	5,410 ¹⁰	55.0
DR 21(OH)	20 39 01.09	42 22 48.90	2,000 ¹¹	-5.0
Cep A East	22 56 18.15	62 01 46.00	700 ¹	-10.1
NGC 7538 IRS 1	23 13 45.34	61 28 10.50	2,650 ¹	-57.3
NGC 7538 IRS 9	23 14 01.66	61 27 20.00	2,650 ¹	-57.3

REFERENCES. — (1)Reid et al. 2009 (2)Hirota et al. 2008 (3)Kenyon et al. 1994 (4)Kim et al. 2008 (5)Anthony-Twarog 1982 (6)Chen et al. 1993 (7)Rygl et al. 2010 (8)Kuchar & Bania 1994 (9)Eiroa et al. 2008 (10)Sato et al. 2010 (11)Odenwald & Schwartz 1993

Gradient (LVG) and Local Thermodynamic Equilibrium (LTE) approximations used, as well as source-by-source comparisons to past studies. A detailed discussion of the limitations of measuring density with the $J = 3$ and 4 K -doublet transitions of H_2CO is provided in §6.

2. FORMALDEHYDE AS A HIGH-DENSITY PROBE

Formaldehyde (H_2CO) is a proven tracer of the high-density environs of molecular clouds. It is ubiquitous; H_2CO is associated with 80% of the HII regions surveyed by Downes et al. (1980) and possesses a large number of observationally accessible transitions from centimeter to far-infrared wavelengths. Because H_2CO is a slightly asymmetric rotor molecule, most rotational energy levels are split by this asymmetry into two energy levels. Therefore, the energy levels must be designated by a total angular momentum quantum number, J , the projection of J along the symmetry axis for a limiting prolate symmetric top, K_{-1} , and the projection of J along the symmetry axis for a limiting oblate symmetric top, K_{+1} . This splitting leads to two basic types of transitions: the high-frequency $\Delta J = 1$, $\Delta K_{-1} = 0$, $\Delta K_{+1} = -1$ “ P -branch transitions” and the lower frequency $\Delta J = 0$, $\Delta K_{-1} = 0$, $\Delta K_{+1} = \pm 1$ “ Q -branch” transitions, popularly known as the “ K -doublet” transitions (see discussion in Mangum & Wootten 1993). The P -branch transitions are only seen in emission in regions where $n(\text{H}_2) \gtrsim 10^4 \text{ cm}^{-3}$. The excitation of the K -doublet transitions, however, is not so simple. For $n(\text{H}_2) \lesssim 10^{5.5} \text{ cm}^{-3}$, the lower energy states of the 1_{10} - 1_{11} through 5_{14} - 5_{15} K -doublet transitions become overpopulated due to a collisional selection effect (Evans et al. 1975; Garrison et al. 1975). This overpopulation cools the $J \leq 5$ K -doublets

to excitation temperatures lower than that of the cosmic microwave background, causing them to appear in absorption. For $n(\text{H}_2) \gtrsim 10^{5.5} \text{ cm}^{-3}$, this collisional pump is quenched and the $J \leq 5$ K -doublets are then seen in emission over a wide range of kinetic temperatures and abundances.

3. OBSERVATIONS

The measurements reported here were made using the National Radio Astronomy Observatory (NRAO¹) Green Bank Telescope (GBT) during the periods 2007 January 20-31, February 19, and 2008 July 2. Single pointing measurements were obtained of the 3_{12} - 3_{13} (28.974805 GHz, $\theta_B = 26''$) and 4_{13} - 4_{14} (48.284547 GHz, $\theta_B = 16''$) K -doublet transitions of H_2CO toward a sample of 23 galactic star-forming regions (Table 1). The 29 and 48 GHz measurements were made using the dual-beam Ka- (beam separation 78'') and Q-band (beam separation 58'') receivers, respectively, over 50 MHz of bandwidth sampled by 16,384 channels. The position-switching technique was employed with reference position located 30' west in azimuth from each source position. The correlator configuration produced a spectral channel width of 3.052 kHz, which is approximately 0.03 and 0.02 km s⁻¹ at 29 and 48 GHz, respectively. The 9_2 - 8_1 A⁻ (28.969942 GHz) vibrational transition of CH_3OH was also captured in the Ka-band spectra.

To calibrate the intensity scale of our measurements, several corrections need to be considered:

¹ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Opacity.—Historical opacity estimates based on atmospheric model calculations using ambient pressure, temperature, and relative humidity measurements indicated that τ_0 at 29 and 48 GHz were, respectively, ~ 0.05 and 0.25 during our observations. The respective opacity corrections $\exp[\tau_0 \csc(EL)]$ for the range of source elevations (28 – 75°) averaged 1.069 and 1.485 , and were applied uniformly since the variance due to elevation was less than the absolute uncertainty in amplitude calibration (see below).

Flux.—Assuming point-source emission, one can use the current relation (derived from measurement) for the aperture efficiency

$$\eta_A = 0.71 \exp(-[0.0163\nu(\text{GHz})]^2)$$

to convert antenna temperature to flux density. At 28.97 and 48.28 GHz this yields $\eta_A = 0.568$ and 0.382 , respectively. For elevation 90° and zero atmospheric opacity, $T_A/S = 2.846\eta_A = 1.61$ and 1.09 for 29 and 48 GHz, respectively. These are the degrees Kelvin per Jansky calibration factors used to convert our spectra to flux assuming point-source emission. Incorporating atmospheric opacity and telescope efficiency, we have $T_A^* = T_A \exp(A\tau_0)/\eta_l = 1.08T_A$ (29 GHz) and $1.50T_A$ (48 GHz), where $\eta_l = 0.99$ for the GBT. Finally, using $\eta_{mb} \simeq 1.32\eta_A$, we can write the main beam brightness

temperature as $T_{mb} \simeq T_A^*/\eta_{mb} = 1.45T_A$ (29 GHz) and $2.90T_A$ (48 GHz).

Source Structure.—Since the beam sizes are about 63% different, and we anticipate source sizes comparable to our beam sizes, it is necessary to scale both measurements to the same beam size to properly intercompare them. The beam coupling correction factor for a Gaussian source and a Gaussian beam to a measurement which has already been corrected to the main-beam efficiency scale is:

$$f_{\text{couple}} = \frac{\theta_{\text{source}}^2 + \theta_{\text{beam}}^2}{2\theta_{\text{source}}^2}$$

Therefore, to scale the $J = 3$ T_{mb} measurements ($\theta_{\text{beam}} = 26''$) to a source size equal to the beam size at $J = 4$ ($\theta_{\text{beam}} = 16''$), an additional factor of 1.82 must be applied to the $J = 3$ T_{mb} measurements. With this, we have assumed that each object in our sample spans $16''$. Refer to §6.3 for additional justification of this assumption.

Absolute amplitude calibration.—The GBT absolute amplitude calibration is reported to be 10 – 15% at all frequencies, limited mainly by temporal drifts in the noise diodes used as absolute amplitude calibration standards.

TABLE 2
H₂CO MEASUREMENT RESULTS

Source	Transition	T_A^* ^a (K)	V_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	$\log \left[\frac{N(\text{ortho-H}_2\text{CO})}{\Delta\nu} \right]$ ^b [cm ⁻² (km s ⁻¹) ⁻¹]
W3 IRS 4	4 ₁₃ -4 ₁₄	≤ 0.090 (3σ)	...	...	...
	3 ₁₂ -3 ₁₃	-0.023 ± 0.010	-47.28 ± 0.44	6.66 ± 0.91	$13.17^{+0.16}_{-0.25}$
		-0.068 ± 0.010	-42.53 ± 0.05	1.00 ± 0.12	$13.65^{+0.06}_{-0.07}$
W3(OH)	4 ₁₃ -4 ₁₄	0.216 ± 0.028	-47.56 ± 0.15	6.23 ± 0.15	$14.18^{+0.05}_{-0.06}$
		-0.136 ± 0.028	-44.46 ± 0.15	1.46 ± 0.15	$13.98^{+0.08}_{-0.10}$
	3 ₁₂ -3 ₁₃	0.124 ± 0.014	-47.60^c	6.20^c	14.09 ± 0.05
		-0.284 ± 0.014	-44.50^c	1.50^c	14.45 ± 0.02
		-0.167 ± 0.014	-46.96 ± 0.08	3.20 ± 0.34	$14.22^{+0.3}_{-0.4}$
L1448 IRS 3B	4 ₁₃ -4 ₁₄	≤ 0.202 (3σ)	...	...	...
	3 ₁₂ -3 ₁₃	0.041 ± 0.005	4.85 ± 0.06	1.76 ± 0.13	$13.51^{+0.5}_{-0.6}$
NGC 1333 IRAS 4A	4 ₁₃ -4 ₁₄	0.084 ± 0.031	7.00^c	2.06^c	$13.48^{+0.14}_{-0.20}$
		0.039 ± 0.031	7.00^c	8.50^c	$13.15^{+0.25}_{-0.67}$
	3 ₁₂ -3 ₁₃	0.162 ± 0.006	6.90^c	2.06 ± 0.06	13.85 ± 0.02
		0.033 ± 0.006	6.90^c	8.50^c	$13.16^{+0.07}_{-0.08}$
		-0.118 ± 0.006	7.50^c	2.00^c	13.71 ± 0.02
NGC 1333 IRAS 4B	4 ₁₃ -4 ₁₄	0.133 ± 0.029	7.08 ± 0.09	2.25 ± 0.26	$13.83^{+0.09}_{-0.11}$
	3 ₁₂ -3 ₁₃	0.036 ± 0.009	6.90^c	2.20^c	$13.40^{+0.10}_{-0.13}$
					$13.82^{+0.14}_{-0.21}$
L1551 IRS 5	4 ₁₃ -4 ₁₄	0.103 ± 0.039	6.51 ± 0.07	0.48 ± 0.14	13.65 ± 0.05
	3 ₁₂ -3 ₁₃	0.050 ± 0.006	6.34 ± 0.03	0.73 ± 0.08	15.19 ± 0.02
Orion-KL	4 ₁₃ -4 ₁₄	1.748 ± 0.064	10.27 ± 0.02	1.72 ± 0.04	15.12 ± 0.05
		0.551 ± 0.064	6.71 ± 0.14	13.53 ± 0.46	14.92 ± 0.03
		0.938 ± 0.064	8.30^c	2.71 ± 0.17	14.93 ± 0.01
	3 ₁₂ -3 ₁₃	0.670 ± 0.016	10.41 ± 0.001	1.62 ± 0.003	15.32 ± 0.01
		0.563 ± 0.016	6.72 ± 0.03	9.58 ± 0.004	15.71 ± 0.01
		3.972 ± 0.016	8.16^c	2.46 ± 0.003	13.95 ± 0.02
Orion-N	3 ₁₂ -3 ₁₃	0.259 ± 0.012	9.37 ± 0.02	1.47 ± 0.05	14.70 ± 0.02
Orion-S	4 ₁₃ -4 ₁₄	0.793 ± 0.035	6.57^c	2.68 ± 0.09	$14.19^{+0.06}_{-0.07}$
		0.243 ± 0.035	6.90^c	6.35 ± 0.40	14.70 ± 0.01
	3 ₁₂ -3 ₁₃	0.575 ± 0.011	6.39^c 0.00	2.65 ± 0.04	$14.10^{+0.03}_{-0.04}$
		0.143 ± 0.011	6.72^c	6.35^c	$13.98^{+0.06}_{-0.07}$
OMC-2 IRS 4	4 ₁₃ -4 ₁₄	0.175 ± 0.026	11.57 ± 0.05	1.66 ± 0.13	$13.65^{+0.05}_{-0.06}$
	3 ₁₂ -3 ₁₃	0.060 ± 0.008	11.50 ± 0.12	1.41 ± 0.05	14.27 ± 0.01
		0.253 ± 0.008	11.36 ± 0.01	6.06 ± 0.49	$13.26^{+0.29}_{-1.30}$
IRAS 05338-0624	4 ₁₃ -4 ₁₄	0.030 ± 0.029	9.60^c	2.48^c	

TABLE 2 — *Continued*

Source	Transition	T_A^* ^a (K)	V_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	$\log \left[\frac{N(\text{ortho-H}_2\text{CO})}{\Delta\nu} \right]$ ^b [cm ⁻² (km s ⁻¹) ⁻¹]
NGC 2024	3 ₁₂ -3 ₁₃	0.075 ± 0.029	7.08 ^c	1.94 ^c	13.65 ^{+0.14} _{-0.21}
		0.019 ± 0.008	9.60 ^c	2.48 ^c	13.21 ^{+0.15} _{-0.24}
		0.070 ± 0.008	7.08 ^c	1.94 ^c	13.77±0.05
NGC 2024 FIR 5	4 ₁₃ -4 ₁₄	0.149 ± 0.038	11.50 ± 0.08	1.25 ± 0.19	13.95 ^{+0.10} _{-0.13}
NGC 2024 FIR 6	4 ₁₃ -4 ₁₄	0.202 ± 0.041	11.20 ^c	1.97 ± 0.19	14.34 ^{+0.08} _{-0.10}
	3 ₁₂ -3 ₁₃	0.224 ± 0.008	11.10 ^c	2.04 ± 0.05	14.55±0.01
		-0.062 ± 0.008	9.10 ^c	0.58 ± 0.06	13.99±0.06
NGC 2071 IR	4 ₁₃ -4 ₁₄	0.108 ± 0.030	11.12 ± 0.12	2.56 ± 0.27	13.55 ^{+0.11} _{-0.14}
	3 ₁₂ -3 ₁₃	0.208 ± 0.011	11.10 ^c	2.14 ± 0.07	13.89±0.02
		-0.044 ± 0.011	9.11 ± 0.12	0.57 ± 0.11	13.21 ^{+0.10} _{-0.13}
S255N	4 ₁₃ -4 ₁₄	0.097 ± 0.040	8.33 ^c	4.79 ± 1.00	13.69 ^{+0.15} _{-0.23}
	3 ₁₂ -3 ₁₃	0.155 ± 0.040	9.81 ± 0.13	1.70 ± 0.39	13.90 ^{+0.10} _{-0.13}
		0.085 ± 0.008	8.33 ± 0.18	4.73 ± 0.27	13.77±0.04
G34.26+0.15	4 ₁₃ -4 ₁₄	0.175 ± 0.008	9.58 ± 0.03	1.84 ± 0.12	14.08±0.02
	3 ₁₂ -3 ₁₃	-0.043 ± 0.008	16.17 ± 0.09	1.94 ± 0.26	13.48 ^{+0.07} _{-0.09}
		0.181 ± 0.019	8.87 ± 0.05	2.94 ± 0.12	13.92 ^{+0.04} _{-0.05}
S68N	4 ₁₃ -4 ₁₄	0.192 ± 0.008	8.79 ± 0.02	2.92 ± 0.06	14.06±0.02
W51M	4 ₁₃ -4 ₁₄	0.147 ± 0.053	57.72 ± 0.24	5.15 ± 0.63	14.20 ^{+0.13} _{-0.19}
DR 21(OH)	4 ₁₃ -4 ₁₄	0.119 ± 0.040	7.85 ± 0.19	4.18 ± 0.42	13.58 ^{+0.13} _{-0.18}
	3 ₁₂ -3 ₁₃	0.251 ± 0.080	56.44 ± 0.25	8.28 ± 0.55	14.40 ^{+0.12} _{-0.17}
		0.320 ± 0.034	-4.22 ± 0.06	3.02 ± 0.14	14.54 ^{+0.04} _{-0.05}
Cep A East	4 ₁₃ -4 ₁₄	0.345 ± 0.034	-1.28 ^c	3.40 ^c	14.04 ^{+0.04} _{-0.05}
	3 ₁₂ -3 ₁₃	0.247 ± 0.005	-4.45 ± 0.04	2.89 ± 0.06	14.59±0.01
		0.182 ± 0.005	-1.28 ± 0.06	3.40 ± 0.11	13.76±0.01
NGC 7538 IRS 1	4 ₁₃ -4 ₁₄	0.078 ± 0.033	-10.40 ^c	2.40 ^c	13.50 ^{+0.15} _{-0.24}
	3 ₁₂ -3 ₁₃	0.042 ± 0.033	-10.28 ± 0.59	6.00 ^c	13.23 ^{+0.25} _{-0.66}
		0.036 ± 0.007	-10.43 ± 0.10	2.43 ± 0.23	13.27 ^{+0.07} _{-0.09}
NGC 7538 IRS 9	4 ₁₃ -4 ₁₄	0.111 ± 0.028	-57.70 ± 0.14	4.18 ± 0.36	14.25 ^{+0.10} _{-0.13}
	3 ₁₂ -3 ₁₃	-0.102 ± 0.009	-59.00 ^c	2.19 ± 0.13	14.39±0.04
		0.110 ± 0.009	-57.65 ^c	4.00 ^c	14.43 ^{+0.03} _{-0.04}
		≤ 0.133 (3σ)	...	...	...
		0.048 ± 0.009	-56.82 ± 0.12	3.31 ± 0.29	13.39 ^{+0.07} _{-0.09}

^a Source radiation temperature corrected for telescope efficiency and atmospheric attenuation. Main beam efficiency and beam dilution calibrations applied for analysis (see §3).

^b LTE approximation. See §5.2 for details.

^c Quantity fixed in Gaussian fit.

4. RESULTS

Both transitions were detected in 15 of the 23 sources in our sample. Three objects yielded nondetections in the $J = 4$ transition (W3 IRS 4, L1448 IRS 3B, and NGC 7538 IRS 9) and another five sources were observed in only one of the two transitions due to time constraints. Data reduction was accomplished using the CLASS (Continuum and Line Analysis Single-dish Software) package from GILDAS². The following spectra have been smoothed to 0.2526 km s⁻¹ (3₁₂-3₁₃) and 0.1516 km s⁻¹ (4₁₃-4₁₄) to increase the signal-to-noise ratio of the individual channels. Each line profile was fitted with 1–3 Gaussian components, and each velocity component was checked for consistency with previous measurements (see §5.4).

Table 2 lists the peak intensity (T_A^*), velocity of the local standard of rest (V_{LSR}), and velocity width at the half maximum (FWHM) determined via Gaussian fitting

for each object. LTE column densities are also listed (see §5.2). Note that the peak intensities quoted in Table 2 are given in the T_A^* scale in the event that a reader may wish to apply calibration factors different than those used in our analysis (see §3). The spectra for sources detected in both the 3₁₂-3₁₃ and 4₁₃-4₁₄ transitions are displayed in Figure 1, while spectra from sources detected or observed in only one of the two transitions are shown in Figure 2.

The 9₂-8₁ A⁻ transition of CH₃OH was detected in 6 sources. Since no further analysis is presented, Gaussian components were not fit to each spectrum and the basic line parameters, determined via direct measurement of the line peak and width, are listed in Table 3 with the spectra displayed in Figure 3. Maser emission of this transition was detected toward one source, W3(OH).

5. ANALYSIS

5.1. Spatial and Column Density Derivation from LVG Modelling

To derive the spatial density [H_2 number density, $n(\text{H}_2)$] and ortho-H₂CO column density in our sample of galactic star-forming regions, we have used a model which incorporates the Large Velocity Gradient (LVG) approximation (Sobolev 1960) to radiative transfer in molecular clouds. The detailed properties of our imple-

² <http://www.iram.fr/IRAMFR/GILDAS/>

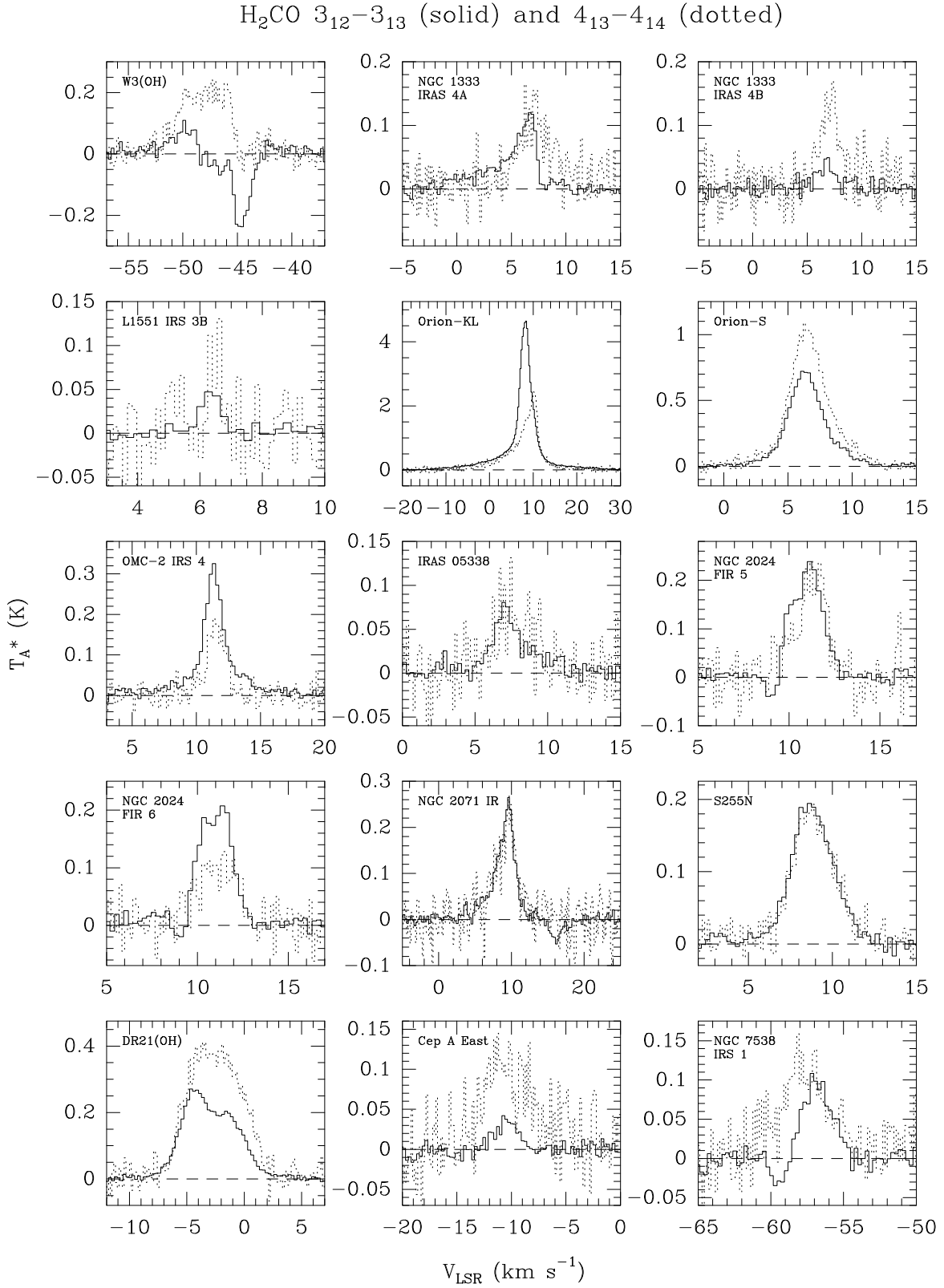


FIG. 1.— Spectra for sources toward which both transitions were detected.

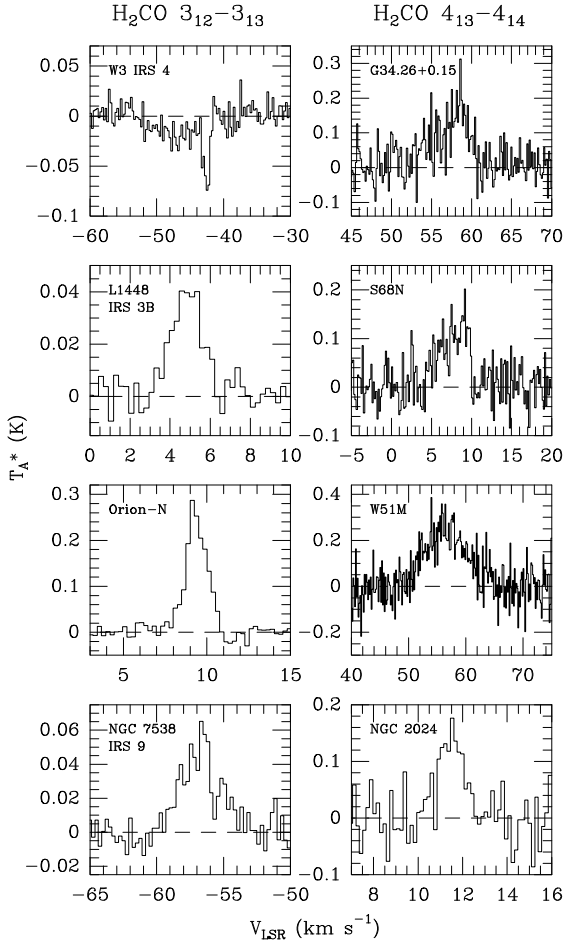


FIG. 2.— Spectra for sources toward which only one transition was detected or observed.

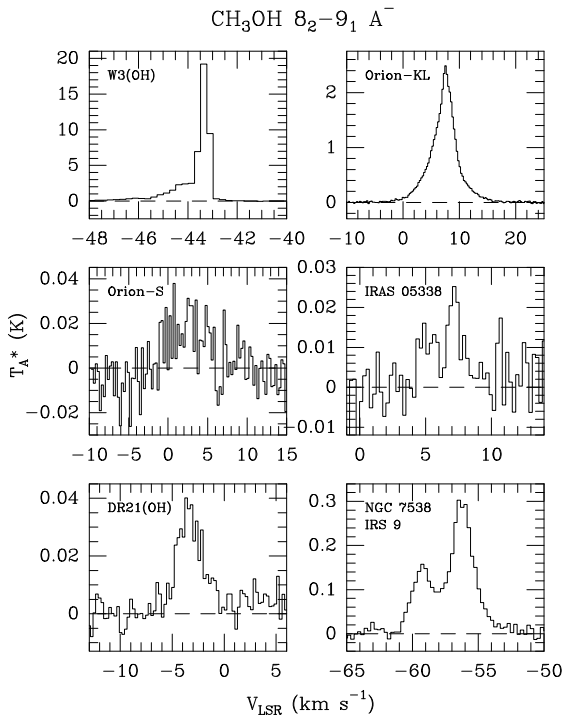


FIG. 3.— Methanol spectra.

mentation of the LVG approximation are described in Mangum & Wootten (1993). In short, the model is used to predict the individual brightness temperatures of both the $J = 3$ and 4 transitions as well as the “transition ratio,” $R_i = \int T_{mb}(3_{12} - 3_{13})d\nu / \int T_{mb}(4_{13} - 4_{14})d\nu$, for a given set of physical conditions: spatial density, column density, kinetic temperature, and optical depth. The solution is then indicated by the intersection of the brightness temperature and R_i predictions. This is illustrated by Figure 4, which is discussed in more detail at the end of this section. It is important to note the behavior of the transition ratio. Since we calculate R_i as (lower excitation)/(higher excitation), a higher ratio implies lower spatial density and/or kinetic temperature. As noted by Mangum & Wootten (1993), one of the major sources of uncertainty in an LVG model prediction of physical conditions is the uncertainty associated with the collisional excitation rates used.

Our model incorporates the scaled excitation rates involving H_2CO and He calculated by Green (1991). An important point regarding our implementation of the LVG model is the scaling of the calculated H_2CO/He excitation rates to those appropriate for collisions with H_2 . Following the recommendation of Green (1991), we scale the calculated He rates by a factor of 2.2 to account for (1) the reduced collision velocity of He relative to H_2 , which scales as the inverse-square-root of the masses of He and H_2 , and (2) the larger cross section of the H_2 molecule (~ 1.6 ; Nerf 1975) relative to He. With these scaling factors, Green (1991) suggests that the total collisional excitation rate for a given H_2CO transition is accurate to $\sim 20\%$. Thus the physical conditions predicted by our LVG model are limited to an accuracy of no better than 20%. It should be noted that the collision rates of H_2CO with H_2 have been rederived with a claimed accuracy of 10% by Troscompt et al. (2009), though only for temperatures < 30 K.

It is also important to note that the LVG model for the $3_{12}-3_{13}$ and $4_{13}-4_{14}$ transitions of H_2CO is somewhat dependent on kinetic temperature (T_K). As such, it was important in this study to carefully select temperature estimates from the literature that best reflect the material being traced by our observations. The temperatures used can be found with their object references in §5.4. The T_K dependence of the LVG model and its effect on our measurements is explored in detail in §6.1.

LVG results for the 15 sources toward which both transitions were detected are displayed in Table 4. A range of derived densities based on the range in our adopted kinetic temperatures is provided in column 5 to illustrate the kinetic temperature dependence of the LVG model. In absence of error bars on the T_K values assumed from the literature, a range of $\pm 50\%$ was used. Column 6 includes the range of density estimates found in selected literature (see §5.4). Note that the uncertainties associated with our results reflect only measurement error. Additional uncertainties associated with our kinetic temperature and spatial extent assumptions are described in §6.

For 6 of 21 velocity components, the observed transition ratio [$R_i = \int T_{mb}(3_{12} - 3_{13})d\nu / \int T_{mb}(4_{13} - 4_{14})d\nu$] and brightness temperatures (T_{mb}) were not consistent with LVG predictions and a Local Thermodynamic Equilibrium (LTE) approximation was employed to place a

limit on the density (see §5.2). In general, this occurred when the R_i was low (< 1), meaning that the higher excitation $J = 4$ transition was unexpectedly observed to be significantly brighter than the $J = 3$. Figure 4 displays $|\text{LVG Prediction} - \text{Observation}|$ for the transition ratio and $J = 4$ brightness temperature in units of the measurement error σ for two sources. OMC-2 IRS 4 (left panel) is indicative of those sources with observed $R_i \sim$

1–2 for which the density could be fully constrained. The solution is indicated by the intersection of the violet and shaded ($< 1\sigma$) regions. Cep A East (right panel) is representative of those objects with ratios $\lesssim 1$. Note how the color and solid-line contours are parallel. Further discussion of the reasons for these failed model fits is given in §6.

TABLE 3
CH₃OH 9₂–8₁ A⁺ MEASUREMENT RESULTS

Source	T_A^* (K)	V_{LSR} (km s ⁻¹)	FWZI (km s ⁻¹)	$\int T_A^* d\nu$ (K km s ⁻¹)
W3(OH) ^a	19.211 ± 0.014	-43.40 ± 0.01	3.06 ± 0.01	12.093 ± 0.012
Orion-KL ^a	2.483 ± 0.016	7.53 ± 0.01	18.18 ± 0.04	11.089 ± 0.034
Orion-S	0.025 ± 0.011	2.39 ± 0.40	12.63 ± 0.82	0.104 ± 0.020
IRAS 05338-0624	0.021 ± 0.008	7.19 ± 0.36	9.73 ± 0.91	0.061 ± 0.013
DR21(OH)	0.036 ± 0.005	-3.28 ± 0.09	9.22 ± 0.23	0.115 ± 0.008
NGC 7538 IRS 9 ^a	0.292 ± 0.009	-56.20 ± 0.02	8.82 ± 0.06	0.977 ± 0.013

^a Multiple velocity components present. See Figure 3 for spectra.

5.2. LTE Approximation

To supplement the LVG model and provide a useful check on its results, a Local Thermodynamic Equilibrium (LTE) approximation to the column density, $N(\text{ortho} - \text{H}_2\text{CO})/\Delta\nu \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$, has been calculated for each velocity component detected (listed in Table 2):

$$N = \frac{3k}{8\pi\nu S\mu^2} \frac{Q_{\text{rot}}}{g_u g_K g_{\text{nuclear}}} \exp\left(\frac{E_u}{kT_{\text{ex}}}\right) \times T_{\text{mb}}$$

$$Q_{\text{rot}} = \frac{1}{3} \left(\frac{\pi k^3}{h^3 A B^2} \right)^{1/2} T^{3/2}, hA \ll kT$$

where the line strength $S = \frac{1}{12}$ ($J = 3$), $\frac{1}{20}$ ($J = 4$); dipole moment $\mu = 2.331$ debye; rotational degeneracy $g_u = 7$ ($J = 3$), 9 ($J = 4$); K degeneracy $g_K = 2$ (for $K \neq 0$ in symmetric top molecules); nuclear spin degeneracy $g_{\text{nuclear}} = 3$ (for ortho-H₂CO); level energy above ground $E_u = 33.479$ K ($J = 3$), 47.928 K ($J = 4$). Note that the peak intensity (T_{mb}) is used instead of integrated intensity to give column density *per unit line width* for consistency with the LVG model results. Note also that the LTE approximation assumes optically thin emission with excitation temperature equivalent to kinetic temperature.

The former assumption is reasonable given that H₂CO transitions rarely become optically thick due principally to fairly low abundances. This property, in part, makes H₂CO an ideal probe of the dense regions within molecular clouds (see §2). Given the average physical conditions derived for our sample [$n(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$, $N(\text{ortho} - \text{H}_2\text{CO})/\Delta\nu \sim 10^{14} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$, $T_K = 100$ K], the LVG-predicted optical depth (τ) ~ 0.078 . The maximum value found for our sample is 0.27, and transitions can generally be considered optically thin for $\tau < 0.4$.

The second assumption that $T_{\text{ex}} = T_K$ is more troublesome. For $n(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$ and

$N(\text{ortho} - \text{H}_2\text{CO})/\Delta\nu \sim 10^{14} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$, the excitation temperatures for the $J = 3$ and 4 K -doublets are on order $\frac{T_K}{10}$ K, while $T_{\text{ex}} \sim \frac{T_K}{2}$ K for the $\Delta J = 1$, $\Delta K_{-1} = 0$, $\Delta K_{+1} = -1$ P -branch transitions. Therefore, since the ortho-H₂CO column density is mainly dependent upon the excitation temperature of the P -branch transitions, $T_{\text{ex}} \lesssim T_K$ for our sample and the resulting LTE column densities must then, strictly speaking, be considered upper limits given that $T_{\text{mb}} \propto T_{\text{ex}}(1 - \exp(-\tau))$. Nevertheless, the LTE-predicted column densities are generally within a factor of 2 of the LVG results (see §5.3 for more details). We consider the LTE approximation to be a reasonable one in cases where the LVG model failed to fully constrain the physical conditions. See §5.4 for kinetic temperature assumptions (alternatively, Tables 4–6).

For those cases (described in the previous section) in which LVG modeling was unsuccessful, the unique properties of the K -doublet transitions discussed in §2 were used to place a limit on the spatial density. A column density was assumed using the LTE approximation described above, and the LVG model was then employed to determine the minimum density required for both transitions to be observed in emission.

The LTE approximation was used in a similar manner for the 12 velocity components detected in only one of the two observed transitions. With the exception of Cep A East, these components were detected in the 3₁₂–3₁₃ transition and not the 4₁₃–4₁₄. If seen in absorption at $J = 3$, the undetected $J = 4$ counterpart must also appear in absorption because of the excitation of the H₂CO molecule. If observed in emission at $J = 3$, the $J = 4$ transition may appear in either state because the 4₁₃–4₁₄ transition is subject to absorption beginning at slightly higher densities (see §6.2 for further detail). The range of densities permitting the $J = 3$ transition to be in emission with the $J = 4$ in absorption is very small, typically spanning 0.2 on the log scale. Rather than dictate this range for each object, we have opted to list just the limit corresponding to the $J = 4$ emission/absorption boundary. Table 5 displays these results.

5.3. Singe Transition H_2CO Column Density Estimates

Observations of only one transition were performed toward 5 sources. For these objects, the LVG model can be used to estimate the ortho- H_2CO column density by assuming a kinetic temperature and spatial density. Ki-

netic temperatures were culled from the literature and can be found with their object references in §5.4. A spatial density of $10^{6.15} \text{ cm}^{-3}$ was assumed based on an average of the results from those sources for which a full LVG analysis could be made. These results are presented in conjunction with the LTE approximation for comparison in Table 6.

TABLE 4
LVG RESULTS: VELOCITY COMPONENTS DETECTED IN BOTH TRANSITIONS

Source	$\frac{\int T_{mb}(3_{12} - 3_{13})d\nu}{\int T_{mb}(4_{13} - 4_{14})d\nu}$	T_K^a (K)	T_{Best}	$\log[n(H_2)]$ (cm^{-3})		$\log\left[\frac{N(\text{ortho-}H_2CO)}{\Delta\nu}\right]$ [$\text{cm}^{-2} (\text{km s}^{-1})^{-1}$]	
				T_{Range}	Literature ^b	$3_{12}-3_{13}$	$4_{13}-4_{14}$
W3(OH) _{emission} ^c	0.73±0.03	110 ⁺⁵ ₋₁₅	≥4.92 ^{+0.02} _{-0.06}	≥4.88–5.00	5.95	14.09±0.05	14.18 ^{+0.05} _{-0.06}
W3(OH) _{absorption}	2.70±0.33	60±20	4.11±0.05	3.97–4.21	4.70	14.64 ^{+0.09} _{-0.18}	14.64±0.07
NGC 1333 IRAS 4A ^d	1.53±0.15	50	6.20 ^{+0.18} _{-0.11}	5.87–7.07	5.48–6.30	13.73 ^{+0.03} _{-0.01}	13.89 ^{+0.08} _{-0.07}
NGC 1333 IRAS 4B ^c	0.34±0.06	80	≥5.31 ^{+0.09} _{-0.05}	≥5.10–5.62	5.48–6.30	13.40 ^{+0.10} _{-0.13}	13.83 ^{+0.09} _{-0.11}
L1551 IRS 5	0.93±0.33	100 ⁺⁵⁰ ₋₆₀	6.87 ^{+1.13} _{-0.76}	6.49–>8.00	5.78–7.04	13.47 ^{+0.03} _{-0.07}	13.64 ^{+0.14} _{-0.21}
Orion-KL _{hot core}	0.92±0.02	300 ₋₇₀	5.97 ^{+0.10} _{-0.09}	6.08	5.70–6.95	14.57 ^{+0.03} _{-0.01}	14.42 ^{+0.05} _{-0.08}
Orion-KL _{compact ridge} ^c	4.85±0.12	135 ⁺²⁵ ₋₁₅	...	...	5.50–5.70	15.71±0.01	14.93±0.03
Orion-KL _{extended ridge} ^c	0.45±0.01	135 ⁺²⁵ ₋₁₅	...	...	> 5.00	14.93±0.01	15.19±0.02
Orion-S _{peak}	0.91±0.02	100	7.21 ^{+0.79} _{-0.40}	6.43–>8.00	6.60–7.78	14.61±0.01	14.61 ^{+0.04} _{-0.01}
Orion-S _{wing} ^c	0.74±0.03	100	≥4.96 ^{+0.02} _{-0.04}	≥4.66–5.26	...	14.10 ^{+0.03} _{-0.04}	14.19 ^{+0.06} _{-0.07}
OMC-2 IRS 4	1.55±0.12	85 ⁺²⁵ ₋₁₀	5.51±0.09	5.37–5.59	5.65–6.28	14.23±0.01	14.19 ^{+0.03} _{-0.05}
IRAS 05338-0624 ^d	1.05±0.16	95±55	6.49 ^{+1.51} _{-0.30}	6.20–>8.00	5.30–6.00	13.59±0.05	13.51 ^{+0.14} _{-0.19}
NGC 2024 FIR 5	1.45±0.13	160 ⁺⁹⁰ ₋₆₀	5.41 ^{+0.11} _{-0.12}	5.31–5.57	5.95–6.00	14.13±0.01	14.15 ^{+0.05} _{-0.07}
NGC 2024 FIR 6	2.03±0.23	40(<160)	5.83 ^{+0.11} _{-0.07}	4.94	5.95–6.30	14.07 ^{+0.01} _{-0.03}	14.03 ^{+0.05} _{-0.09}
NGC 2071 IR _{peak}	1.54±0.19	80 ⁺²⁰ ₋₁₅	5.71 ^{+0.18} _{-0.14}	5.57–5.85	5.48–6.48	14.03±0.01	14.05 ^{+0.08} _{-0.09}
NGC 2071 IR _{wing}	1.09±0.13	80 ⁺²⁰ ₋₁₅	6.53 ^{+0.52} _{-0.26}	6.34–6.73	> 5.00	13.59 ^{+0.03} _{-0.05}	13.57 ^{+0.15} _{-0.22}
S255N	1.33±0.06	70±30	6.02 ^{+0.09} _{-0.05}	5.78–6.58	6.48–7.20	13.97 ^{+0.02} _{-0.01}	13.97 ^{+0.04} _{-0.03}
DR 21(OH) _{MM1}	0.93±0.04	160 ⁺¹⁴⁰ ₋₉₀	6.34 ^{+0.16} _{-0.13}	6.04–>8.00	5.80–6.10	14.17±0.01	14.16 ^{+0.05} _{-0.06}
DR 21(OH) _{MM2} ^c	0.67±0.02	30(<60)	≥5.58±0.08	≥5.36	7.00–7.83	13.76±0.01	14.04 ^{+0.04} _{-0.05}
Cep A East ^c	0.58±0.11	70 ⁺³⁰ ₋₃₀	≥5.42 ^{+0.02} _{-0.04}	≥5.30–5.91	6.30–6.78	13.27 ^{+0.07} _{-0.09}	13.50 ^{+0.15} _{-0.24}
NGC 7538 IRS 1	1.20±0.10	220 ⁺³⁰ ₋₄₀	5.78 ^{+0.15} _{-0.12}	5.75–5.83	5.30–7.00	13.75 ^{+0.03} _{-0.05}	13.73 ^{+0.09} _{-0.12}

^a Culled from the literature; in absence of error estimates, a range of ±50% was tested. See §5.4 for references.

^b Spatial density range found in selected literature. See §5.4 for references.

^c Full LVG modeling was unsuccessful; LTE approximated column density quoted. See §5.2 for details on limit derivation.

^d Total integrated emission used; see §5.4.4 & §5.4.9 for details.

5.4. Comparison to Previous Measurements

What follows are very brief descriptions of past studies of the objects in our sample that were most relevant to our analysis. This section also includes accounts of any peculiarities in our spectra that resulted in steps additional to those described above, notably NGC 1333 IRS 4A, Orion-KL, IRAS 05338-0624, NGC 2071 IR, and DR21(OH). Much has been published on these objects; readers seeking additional information should follow the citations below.

5.4.1. W3 IRS 4

Embedded infrared source with associated compact HII Region W3(C) (Wynn-Williams et al. 1972). Our spectra found two velocity components at -47.3 and -42.5 km s^{-1} in the $3_{12}-3_{13}$ transition, consistent with the

$1_{10}-1_{11}$ and $2_{11}-2_{12}$ H_2CO observations of Dickel et al. (1996), but failed to detect the $4_{13}-4_{14}$ transition. LVG modeling of several H_2CO transitions from 211–365 GHz was employed by Mangum & Wootten (1993) to find $T_K = 75^{+20}_{-15}$ K and $\log[n(H_2)] = 5.40^{+0.10}_{-0.20} \text{ cm}^{-3}$, while Helmich et al. (1994) found $T_K = 55^{+20}_{-10}$ K and $n(H_2) = 10^6 \text{ cm}^{-3}$ in a study using several molecules, including four H_2CO transitions at around 364 GHz.

5.4.2. W3(OH)

Compact HII region with a shell structure (Dreher & Welch 1981) surrounding an embedded infrared source with characteristics of a young O star (Campbell et al. 1989) and extensive maser activity (e.g. Moscadelli et al. 2010; Figure 3 of this paper). Mauersberger et al. (1988) detected a warm molecular core and red-shifted emission feature using NH_3 with central velocity $\sim -47 \text{ km s}^{-1}$. Absorption features, red-shifted with respect to the main emission component, have also been observed in HCO^+ and OH (Wink et al. 1994; Baudry & Menten 1995). The dominant emission and absorption components are detected by both our $4_{13}-4_{14}$ and $3_{12}-3_{13}$ spectra. The $J = 3$ absorption profile exhibits an additional velocity component at

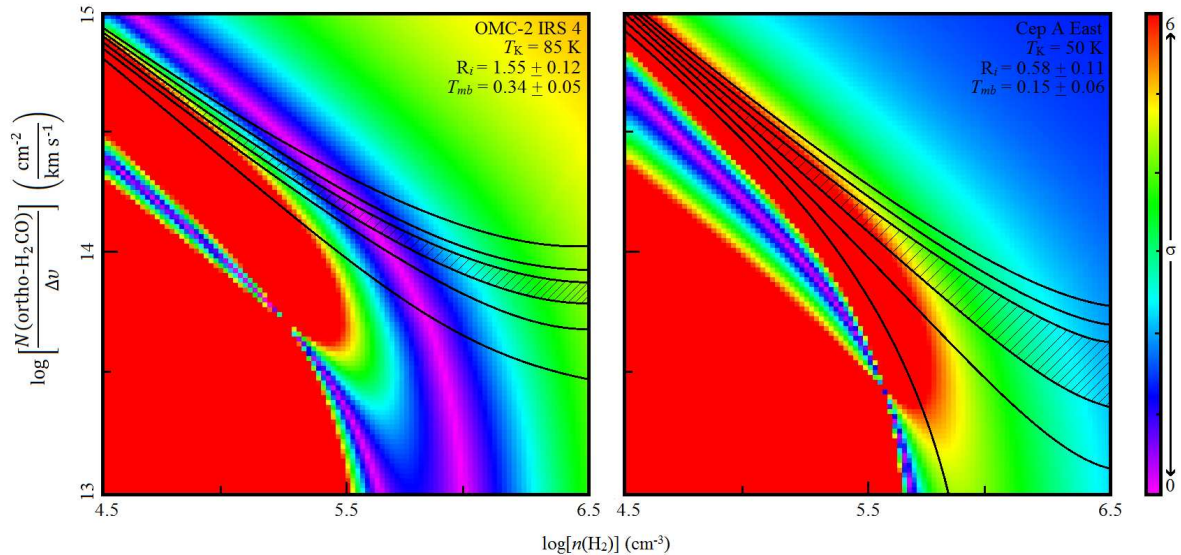


FIG. 4.— Comparison of model results for representative examples of the 15 velocity components with transition ratios (R_i) ~ 1 –2 that were well-fit (left panel) and the remaining 6 components with ratios $\lesssim 1$ whose observed profiles were inconsistent with LVG predictions (right panel). Color: |LVG Prediction – Observation| for the integrated intensity ratio R_i (3_{12} – 3_{13} / 4_{13} – 4_{14}) in units of the measurement error σ from $< 1\sigma$ (violet) to $> 6\sigma$ (red). Contours: |LVG Prediction – Observation| for the 4_{13} – 4_{14} brightness temperature T_{mb} in units of σ ; shaded region corresponds to $\leq 1\sigma$. Observed values listed in the upper right of each panel. Model solution indicated by the intersection of the violet and shaded regions.

47.0 km s^{-1} , which dominates the 2 and 6 cm H_2CO observations of Dickel & Goss (1987). The absence of this component from our $J = 4$ spectrum is indicative of a foreground absorbing layer. Mangum & Wootten (1993) used LVG modeling of several H_2CO transitions from 211–365 GHz to find $T_K = 110^{+5}_{-15}$ K and $\log[n(\text{H}_2)] = 5.95^{+0.05}_{-0.01} \text{ cm}^{-3}$ for the emitting material, while Dickel & Goss (1987) suggest that the H_2CO absorption likely arises from material of density $\sim 5 \times 10^4 \text{ cm}^{-3}$ assuming a temperature of 60 K based on the work of Guilloteau et al. (1983). They note that 60 K likely represents an upper limit to the temperature of the H_2CO absorption region and also test 40 K to demonstrate the temperature dependency of their procedure.

5.4.3. L1448 IRS 3B

3A and 3B are Class 0 sources separated by $6''$ that share a common envelope in a potential protobinary system (Barsony et al. 1998), of which 3B dominates at mm wavelengths (Terebey & Padgett 1997). H^{13}CO^+ and N_2H^+ observations by Volgenau et al. (2006) indicate a systemic velocity between 3.4 – 5.8 km s^{-1} , consistent with our 3_{12} – 3_{13} observation ($V_{\text{LSR}} = 4.8 \text{ km s}^{-1}$). The 4_{13} – 4_{14} transition was not detected. Maret et al. (2004) employed LVG modeling of several H_2CO transitions from 141–364 GHz to find $T_K = 90 \text{ K}$ and $n(\text{H}_2) = 10^5 \text{ cm}^{-3}$.

5.4.4. NGC 1333 IRAS 4A and B

Premier examples of embedded, low mass star formation. Separated by $\sim 30''$, 4A and B are the brightest of three sources in the IRAS 4 core (Sandell et al. 1991) and each have independently been resolved into binary systems (Looney 1998; Looney et al. 2000). P Cygni profiles, indicative of infall and characterized by a blueshifted emission component and redshifted absorption, have been detected toward both cores in interfero-

metric observations of H_2CO (3_{12} – 2_{11} , 226 GHz) and CS (Di Francesco et al. 2001). This profile is eschewed in all but our 3_{12} – 3_{13} observations of IRAS 4A, which indicates an absorption component at 7.5 km s^{-1} with two emission components at $\sim 7.0 \text{ km s}^{-1}$ being detected in both transitions. The broader, wing component of the emission can be attributed to outflow material. The absorption feature in the 3_{12} – 3_{13} spectrum of IRAS 4A has the effect of bisecting the Gaussian profiles of both emission components, eliminating the high velocity component of the profile detected in the 4_{13} – 4_{14} transition but without bringing the net $J = 3$ profile below the baseline. Because of the blending in this spectrum, the total integrated emission over the FWZI of the entire line profile for IRAS 4A has been used for our analysis with the integrated intensity from the Gaussian fit to the absorption component added to the total $J = 3$ intensity.

The observations toward IRAS 4B were well fit by single Gaussians between 6.9 and 7.1 km s^{-1} , in agreement with the average systemic velocity of 7.0 km s^{-1} found for the IRAS 4 group by Di Francesco et al. (2001). However, the 3_{12} – 3_{13} emission was anomalously low, resulting in a transition ratio that could not be fit by the LVG model. Based on the aforementioned detection of H_2CO absorption toward 4B within the velocity range over which our emission was observed, it is possible that the $J = 3$ emission is being subtracted by an absorption component not visually reflected in our line profile. This possibility is discussed in detail in §6.3.

Using LVG modeling of several H_2CO transitions from 141–364 GHz, Maret et al. (2004) derived the following properties: 4A– $T_K = 50 \text{ K}$, $n(\text{H}_2) = 3 \times 10^5 \text{ cm}^{-3}$; 4B– $T_K = 80 \text{ K}$, $n(\text{H}_2) = 3 \times 10^5 \text{ cm}^{-3}$. Blake et al. (1995) analyzed a combination of H_2CO (several transitions from 218–365 GHz) and CS line ratios to find $T_K = 20$ – 40 K and $n(\text{H}_2) = 2 \times 10^6 \text{ cm}^{-3}$ for both core components, and $T_K = 70$ – 100 K and $n(\text{H}_2) = 5 \times 10^6 \text{ cm}^{-3}$ for the wing

material near IRAS 4A.

5.4.5. L1551 IRS 5

Low mass star forming site suggested to be a binary system separated by $\sim 0.3''$ (Cohen et al. 1984). Single Gaussian emission profiles were detected in both transitions with a central velocity typical of the region at $\sim 6.4 \text{ km s}^{-1}$. Moriarty-Schieven et al. (1995) used H_2CO ($3_{03}-2_{02}$ and $3_{22}-2_{21}$, 218 GHz) and CS observations to derive a kinetic temperature of $\sim 40 \text{ K}$ and a spatial density of $6.9 \times 10^6 \text{ cm}^{-3}$. Roberts et al. (2002) and Roberts & Millar (2007) examined transition ratios of several species, including the $2_{11}-1_{10}$ (150 GHz) and $5_{14}-5_{15}$ (72 GHz) transitions of H_2CO , and quote a bolometric temperature of 97 K for the region. Because the

H_2CO transitions employed by Moriarty-Schieven et al. (1995) are biased toward temperatures $\leq 50 \text{ K}$ and the LVG prediction of our observed transition ratio supports a higher kinetic temperature, we have assumed 100 K for our analysis while also testing temperatures of 40 and 150 K. Additional H_2CO measurements have been conducted for L1551 for the $1_{10}-1_{11}$ transition by Araya et al. (2006). The spatial density of IRS 5 has been estimated using several methods. Butner et al. (1991) found an average volume density of $9 \times 10^5 \text{ cm}^{-3}$ within an angular radius of $13''.8$ by modeling far-infrared emission, while Fuller et al. (1995) estimate $6 \times 10^5 \text{ cm}^{-3}$ using C^{17}O emission. Moriarty-Schieven et al. (1995) derived the significantly higher density of $11 \times 10^6 \text{ cm}^{-3}$ using transition ratios of the CS molecule.

TABLE 5
LVG RESULTS: VELOCITY COMPONENTS DETECTED IN ONE TRANSITION

Source	T_K^a (K)	$\log \left[\frac{N(\text{ortho-}\text{H}_2\text{CO})}{\Delta\nu} \right]^b$ [$\text{cm}^{-2} (\text{km s}^{-1})^{-1}$]	$\log[n(\text{H}_2)]$ (cm^{-3})
Emission Components			
L1448 IRS 3B	90	13.17	≥ 5.32
OMC-2 IRS 4 _{wing} ^c	85	14.27	$4.93 \leq n \leq 6.66$
Cep A East _{wing}	80	13.23	≥ 5.28
NGC 7538 IRS 9	60	13.39	≥ 5.52
Absorption Components			
W3 IRS 4 _{peak}	75	13.65	≤ 5.50
W3 IRS 4 _{wing}	75	13.17	≤ 5.36
W3(OH)	60	14.22	≤ 5.13
NGC 1333 IRAS 4A	50	13.71	≤ 5.52
NGC 2024 FIR 5	25	13.99	≤ 5.58
NGC 2024 FIR 6	25	13.21	≤ 5.84
NGC 2071 IR	80	13.48	≤ 5.38
NGC 7538 IRS 1	25	14.43	≤ 5.17

^a Culled from the literature. See §5.4 for references.

^b LTE approximation.

^c For this source only, the 3σ detection limit could be used to determine upper and lower limits.

5.4.6. Orion-KL

The best-studied region of massive star formation to date (see review by Genzel & Stutzki 1989) and extremely bright in a plethora of chemical species (brightness temperatures from Orion-KL are $> 5 \times$ that of any other source in our study). This is the only source in our sample for which previous observations of the $3_{12}-3_{13}$ transition of H_2CO have been made (Wilson et al. 1980; Myers & Buxton 1980; Bastien et al. 1985). Outflows, shocks, and turbulence arising from newly formed stars in the region have led to a complex velocity structure comprised of several distinct components (Blake et al. 1987), at least three of which are captured in our observations: the hot core ($V_{\text{LSR}} \sim 6 \text{ km s}^{-1}$, $\Delta\nu > 10 \text{ km s}^{-1}$, $T_K \sim 300 \text{ K}$), compact ridge ($V_{\text{LSR}} \sim 8 \text{ km s}^{-1}$, $\Delta\nu \sim 4 \text{ km s}^{-1}$, $T_K \sim 135 \text{ K}$), and extended ridge ($V_{\text{LSR}} \sim 9-10 \text{ km s}^{-1}$, $\Delta\nu \sim 4 \text{ km s}^{-1}$, $T_K \sim 135 \text{ K}$), each with spatial density $n(\text{H}_2) \gtrsim 10^5 \text{ cm}^{-3}$ (Mangum et al. 1993; Mangum & Wootten 1993).

Our $J = 4$ spectrum exhibits an anomalously intense

velocity component at $V_{\text{LSR}} \sim 10.3 \text{ km s}^{-1}$, which also appears as a much smaller contribution in the $J = 3$ transition. A feature at this velocity exists $10''$ north of our observed position (Mangum et al. 1990), leading us to suspect a pointing error. Pointing was checked prior to observing, and the Orion-KL scan was followed by observations of OMC-2 IRS 4 and NGC 2024. If a pointing error is to be blamed, it should manifest itself in the subsequent observations of OMC-2 IRS 4 and NGC 2024, but we could find no evidence for this. The possibilities of an unidentified line or rest frequency error were also ruled out. This spectrum is the average of only two (mutually consistent) scans conducted during a single run. We suggest that this emission arises from the extended ridge, which is typically observed around $V_{\text{LSR}} \sim 9 \text{ km s}^{-1}$, but occasionally as high as 10 km s^{-1} . This interpretation, and the physical parameters derived from it, should be applied cautiously for the reasons explained above. Because of the disparity between the relative intensity of the 10.3 km s^{-1} feature in each transition, only the transition ratio for the hot core component could be fit by the LVG model, and the extraordinarily high intensities precluded the determination of useful density limits for the other components through the procedure described in §5.2.

5.4.7. Orion-S

Broad SiO emission coupled with relatively weak SO₂ and CH₃OH emission indicates the presence of an energetic outflow in its earliest phase, suggesting that Orion-S is one of the youngest stellar objects in the region (McMullin et al. 1993). Emission from $V_{\text{LSR}} \sim 5.5\text{--}7.5$ km s⁻¹ has been observed in numerous dense gas tracers, including H₂CO by Bastien et al. (1985) (2₁₁-2₁₂, 14 GHz) and Mangum et al. (1990) (several transitions from 218–291 GHz). Additionally, H₂CO absorption has been detected for the 1₁₀-1₁₁ transition by Johnston et al. (1983) over the velocity range 3.7–9.8 km s⁻¹, which Mangum et al. (1993) also detect and attribute to a lower density region just north of the emission features. Using NH₃ data and the 2₁₁-2₁₂ observations of H₂CO that would later be presented by Bastien et al. (1985), Batrla et al. (1983) found a kinetic temperature of 100 K for the 6.5 km s⁻¹ component and a density of 4×10^6 cm⁻³, significantly lower than our result. However, they also detect a separate velocity component within our detected velocity range at 7.4 km s⁻¹ for which they derive a density of 6×10^7 cm⁻³, significantly higher than our result.

We observe both the $J = 4$ and $J = 3$ transitions in emission with peaks at ~ 6.4 km s⁻¹. Both spectra also exhibit broad wing components likely arising from the outflow material. The transition ratio for the wing emission was anomalously low and thus the density could not be fully constrained by the LVG model. Given that H₂CO absorption has been observed over this velocity range, it is possible that the 3₁₂-3₁₃ emission is being partially absorbed without an absorption component being visually reflected in the line profile. This possibility is discussed in detail in §6.3.

TABLE 6
LVG RESULTS: SINGLE TRANSITION OBSERVATIONS

Source	T_K^a (K)	$\log \left[\frac{N(\text{ortho-H}_2\text{CO})}{\Delta\nu} \right]^b$	
		LVG	LTE
Orion-N	35	$14.21^{+0.04}_{-0.02}$	13.95 ± 0.02
NGC 2024	95	$13.81^{+0.09}_{-0.11}$	$13.95^{+0.10}_{-0.13}$
G34.26+0.15	160	$13.80^{+0.14}_{-0.21}$	$14.20^{+0.12}_{-0.19}$
S68N	35	$13.88^{+0.09}_{-0.12}$	$13.58^{+0.13}_{-0.18}$
W51M	150	$14.03^{+0.13}_{-0.17}$	$14.40^{+0.12}_{-0.17}$

^a Culled from the literature. See §5.4 for references.

^b LVG column density derived assuming $n(\text{H}_2) = 10^{6.15}$ cm⁻³, the average density from Table 4. LTE results from Table 2 provided for comparison.

5.4.8. OMC-2 IRS 4

Infrared source composed of two objects designated 4N and 4S, which are separated by $\sim 4''$ (Pendleton et al. 1986) and associated with the extended (29''x13'') source FIR 3 (Mezger et al. 1990). Our observations exhibit Gaussian profiles consistent with the literature and peaked at ~ 11.5 km s⁻¹. The $J = 3$ profile includes an additional wing component that can be attributed to an outflow in the region. Previous LVG modeling of

several H₂CO transitions from 211–365 GHz was conducted by Mangum & Wootten (1993), who found $T_K = 85$ K and $\log[n(\text{H}_2)] = 5.65$ cm⁻³, nearly identical to our result. Mezger et al. (1990) estimated the density of OMC-2 over a 50''x50'' region to be 1.9×10^6 cm⁻³ using inferred mass and source size arguments.

5.4.9. IRAS 05338-0624

Young stellar object associated with L1641-N, a cluster of infrared sources (Strom et al. 1989; Chen et al. 1993) found to be mainly low-mass, pre-main sequence stars (Hodapp & Deane 1993). Chen et al. (1996) used an analysis of CS observations to estimate the density of the molecular core to be $\sim 10^6$ cm⁻³, while McMullin et al. (1994) also used CS to find a density of 2×10^5 cm⁻³ assuming a temperature of 42 K derived from dust continuum observations (Walker et al. 1990). Stanke & Williams (2007) uncovered higher temperatures (~ 150 K) within a 1.''4 region using CH₃CN observations. Since the dust continuum represents, at best, a lower limit to the kinetic temperature of the gas and the high temperatures found by Stanke & Williams (2007) are constrained to an area much smaller than our beam size, we have used an average of 95 K for our analysis and tested both extremes.

Both of our H₂CO spectra exhibit a two-component structure with a central peak at $V_{\text{LSR}} \sim 7.1$ km s⁻¹ and a shoulder profile centered around $V_{\text{LSR}} \sim 9.6$ km s⁻¹. The shoulder profile is attributed to the red lobe of the outflow material and is consistent with the spectra of several species observed by McMullin et al. (1994). Because the shoulder profile is very weakly detected in the $J = 4$ profile, our confidence in the Gaussian fitting routine's ability to reliably separate the two components was low, so the total integrated emission over the FWZI of the entire line profile was used in our analysis.

5.4.10. NGC 2024 FIR 5 and 6

Star forming region containing a string of dense cores, FIR 1-7, embedded in an extended molecular ridge (Mezger et al. 1992). Both transitions were detected toward FIR 5 and 6, and an additional 4₁₃-4₁₄ measurement was made for the ridge material (approximately midway between FIR 4 and 5). The following properties have been derived from LVG modeling of several H₂CO transitions (211–365, 632 GHz): FIR 5– $T_K = 160^{+90}_{-60}$ K, $n(\text{H}_2) = 1 \pm 0.5 \times 10^6$ cm⁻³; FIR 6– $T_K = 40^{+120}_{-10}$ K, $n(\text{H}_2) = 2 \pm 0.5 \times 10^6$ cm⁻³; Ridge– $T_K = 95^{+30}_{-20}$ K (Mangum & Wootten 1993; Mangum et al. 1999; Watanabe & Mitchell 2008).

The absorption feature exhibited by both of our 3₁₂-3₁₃ observations is attributed to a cool (20–30 K) foreground layer, which has been observed in the 1₁₀-1₁₁ and 2₁₁-2₁₂ transitions of H₂CO and found to have $n(\text{H}_2) = 10^{4.9}$ cm⁻³ (Henkel et al. 1982; Crutcher et al. 1986). The physical parameters of NGC 2024 have been explored using a variety of other tracers as well, recently CO by Emprechtinger et al. (2009), who found the bulk of the material to be characterized by $T_K \sim 75$ K and $n(\text{H}_2) \sim 9 \times 10^5$ cm⁻³.

5.4.11. NGC 2071 IR

Cluster of infrared sources spanning $\sim 30''$ (Persson et al. 1981); our observations are centered on IRS 1, but IRS 2 and 3 are also being sampled. Both spectra indicate a central velocity consistent with the literature at $\sim 9.7 \text{ km s}^{-1}$. An additional shoulder component arising from dense gas in the outflow was also detected in both transitions at $\sim 8.3 \text{ km s}^{-1}$, and an absorption component was observed in the $J = 3$ profile at $\sim 16.2 \text{ km s}^{-1}$. The 16 km s^{-1} feature has been previously observed in emission for the CS $J = 1-0$ line by Takano et al. (1984) and Kitamura et al. (1992).

Previous H_2CO measurements of several transitions from 211–365 GHz by Mangum & Wootten (1993) estimate $T_K = 80 \text{ K}$ and $n(\text{H}_2) = 10^6 \text{ cm}^{-3}$. Tauber et al. (1988) used the $3_{13}-2_{12}$ (211 GHz) and $3_{12}-2_{11}$ (225 GHz) transitions of H_2CO to estimate the density in the region and found $n(\text{H}_2) \sim 3 \times 10^5 \text{ cm}^{-3}$. A microturbulent model of CS and C^{34}S emission from Zhou et al. (1990) yielded a best fit to the density at $3 \times 10^6 \text{ cm}^{-3}$ with the density of the outflow emission being $> 10^5 \text{ cm}^{-3}$. Our LVG analysis yielded a significantly higher density for the outflow component than for the central emission peak. It is possible that our two-component Gaussian fit to the spectra is improperly separating the components. An analysis of the total integrated emission over the FWZI of the entire line profile yields $n(\text{H}_2) = 10^{6.00} \text{ cm}^{-3}$.

5.4.12. S255N

Massive star-forming region also known as S255 FIR 1 or G192.60-MM1 that lies at one end of an extended molecular ridge opposite S255IR (Heyer et al. 1989). Three compact cores, SMA1–3, were resolved in the 1.3 mm continuum maps of Cyganowski et al. (2007), who also combined an analysis of H_2CO transition ratios ($3_{03}-2_{02}$, $3_{22}-2_{21}$, and $3_{21}-2_{20}$; 218–219 GHz) and a spectral energy distribution (SED) model to estimate a temperature range of 40–100 K and densities between $3\text{--}16 \times 10^6 \text{ cm}^{-3}$. The H_2CO observations presented in Cyganowski et al. (2007) are centered on either side of SMA1 (NE and SW) and indicate velocity components at $V_{\text{LSR}} \sim 6.9 \text{ km s}^{-1}$ and 12.1 km s^{-1} , while our spectra, centered between the two, show a single component at $\sim 8.9 \text{ km s}^{-1}$.

5.4.13. G34.26+0.15

Ultra compact (UC) HII region with an associated hot core that has become a prototypical example of cometary morphology (Wood & Churchwell 1989; van Buren et al. 1990). The hot molecular gas (80–175 K) is suggested to be the outer layer of a massive, cool core that is being externally heated by the UC HII region, from which it is offset by $\sim 2''$ (Heaton et al. 1989; Watt & Mundy 1999). Single dish CH_3CN observations conducted by Churchwell et al. (1992) suggest gas temperatures of 166 K and densities $> 10^5 \text{ cm}^{-3}$, while Mookerjee et al. (2007) also found a temperature of 160 K using the brightness temperatures of several optically thick lines.

5.4.14. S68N

Deeply embedded source within the Serpens molecular cloud containing a protostar with an associated outflow (Wolf-Chase et al. 1998), suggested by McMullin et al. (2000) to be an example of a “cool core,” with

properties intermediate to cold/warm condensations. McMullin et al. (2000) used relative intensities of four H_2CO transitions [$1_{01}-0_{00}$ (73 GHz), $2_{02}-1_{01}$ (146 GHz), $3_{03}-2_{02}$ (218 GHz), and $3_{22}-2_{18}$ (218 GHz)] to derive a kinetic temperature range of 35–70 K but report flat-topped line profiles suggesting an overestimation due to optical depth effects and adopt an estimate of 35 K for their measurements. Hurt et al. (1996) also examined four H_2CO transitions [$3_{03}-2_{02}$ (218 GHz), $3_{22}-2_{18}$ (218 GHz), $5_{05}-4_{04}$ (363 GHz), $5_{23}-4_{22}$ (365 GHz)] to determine a higher temperature of around 75 K. Both studies also report spatial density estimates with McMullin et al. (2000) finding $n(\text{H}_2) = 0.4\text{--}1.2 \times 10^6 \text{ cm}^{-3}$ using H^{13}CO^+ , SiO, and DCN, while Hurt et al. (1996) found $2.5 \times 10^6 \text{ cm}^{-3}$ using H_2CO .

5.4.15. W51M

Dominant region of the massive star-forming site W51, which Martin (1972) revealed to consist of eight distinct components at centimeter wavelengths. Our observations are centered on W51e, itself divided into four UC HII regions e1–4 (Gaume et al. 1993), whose association with dense molecular cores and maser activity is known as W51-Main (Zhang & Ho 1997). Remijan et al. (2004) used CH_3CN to find temperatures of 123 and 153 toward e1 and e2, respectively, and a density of $5 \times 10^5 \text{ cm}^{-3}$ for both sources. Zhang & Ho (1997) derive higher densities of $2\text{--}3 \times 10^6 \text{ cm}^{-3}$ for the region using NH_3 .

5.4.16. DR21(OH)

Star-forming region in an early phase of its evolution which has yet to see substantial ionization of the molecular material surrounding newly-formed, massive B stars. Mangum et al. (1992) detected four principal condensations labelled M, N, W, and S. Our observations are centered on DR21(OH)-M, which is subdivided into two components separated by $\sim 8''$, MM1 and MM2. Despite their proximity, MM1 and MM2 differ substantially. MM1 is hot ($\sim 160 \text{ K}$), dense ($\sim 10^6 \text{ cm}^{-3}$), and moderately luminous ($\sim 10^4 L_{\odot}$), while MM2 is cooler ($\sim 30 \text{ K}$), denser ($\sim 10^7 \text{ cm}^{-3}$), and less luminous ($\sim 10^3 L_{\odot}$) (Mangum et al. 1991, 1992; Mangum & Wootten 1993). Our $J = 3$ spectrum indicates distinct peaks at -4.5 and -1.3 km s^{-1} , attributed to MM1 and MM2, respectively. The $J = 4$ spectrum is severely blended and demands a surprisingly high contribution from the -1.3 km s^{-1} (MM2) component. Since this region has not been mapped at these frequencies and the spectra were so highly blended, due caution should be exercised when assessing our results.

5.4.17. Cep A East

Massive star forming region known to consist of 16 compact ($\sim 1''$) components clustered within a $25''$ radius and aligned in an inverted Y-shaped structure (Garay et al. 1996). Our observations are centered on the continuum source HW3, $\sim 3''$ south of the dominant source HW2. HW2 is well within our beam and is associated with a promising candidate for the detection of a massive disk (Torrelles et al. 1996; Patel et al. 2005), though other studies suggest that this elongated molecular structure is explained by the superposition of at least three hot cores (Comito et al. 2007; Brogan et al.

2007). Choosing an appropriate kinetic temperature estimate was difficult for this region because of the inclusion of several compact sources within our beam. We have assumed a range of 40–100 K based on the estimates of Brogan et al. (2007) and Codella et al. (2005) for the ambient cloud velocity of $\sim 10.5 \text{ km s}^{-1}$. Codella et al. (2005) also find densities between $2\text{--}6 \times 10^6 \text{ cm}^{-3}$ in the region using SO and SiO.

5.4.18. NGC 7538 IRS 1

The brightest of three compact sources discovered by Martin (1973), which contains a zero-age main sequence star of spectral type earlier than O7.5 (Lugo et al. 2004) embedded in a molecular cloud with an inner shell structure surrounding the star (Pratap et al. 1997). A systemic velocity of around -57 km s^{-1} was observed in several transitions of H_2CO between 365–470 GHz by van der Tak et al. (2000) with an absorption feature near -60 km s^{-1} having been detected in NH_3 (Wilson et al. 1983), both of which are found in our spectra. The region is also notable for the rare occurrence of 6 cm ($1_{10}\text{--}1_{11}$) H_2CO masers (Rots et al. 1981; Hoffman et al. 2003). The absorption component we observe was also detected by Hoffman et al. (2003) in the 2cm ($2_{11}\text{--}2_{12}$) transition of H_2CO .

A temperature of $\sim 220 \text{ K}$ was found using NH_3 by Mauersberger et al. (1988), while a cooler temperature of 176 K was found by Mitchell et al. (1990) using ^{13}CO and a warmer one of 245 K by Qiu et al. (2011) using CH_3CN . The Mitchell study also indicates a cold gas component of 25 K from which the absorption component in our $J = 3$ spectrum likely arises. From ^{13}CO observations, Qiu et al. (2011) estimate the density to be $\sim 10^7 \text{ cm}^{-3}$ for a region about half the size of our beam, while Mitchell et al. (1990) indicate that the density is $> 10^6 \text{ cm}^{-3}$. Hoffman et al. (2003) note that to excite the $1_{10}\text{--}1_{11}$ H_2CO masers in the region, lower densities in the range of $6\text{--}16 \times 10^4 \text{ cm}^{-3}$ are required. The masers arise from a region directly in front of IRS 1 not coincident with the hot core region examined by the previously mentioned authors.

Since our observations are of higher excitation transitions than the H_2CO masers in the Hoffman study, it is likely that we are sampling material from both the hot core and maser regions, and thus the intermediate density we find is justified. However, this notion also calls into question the validity of our kinetic temperature assumption, so it should be noted that temperatures $< 120 \text{ K}$ would result in densities $> 10^6$ in the LVG approximation. That said, due to the excitation requirements of the $3_{12}\text{--}3_{13}$ and $4_{13}\text{--}4_{14}$ transitions compared to that of the $J = 1$ K -doublet observed by Hoffman et al. (2003), it is more likely that our measurements are biased toward the higher temperatures of the hot core. Fortunately, the H_2CO LVG models are relatively independent of T_K for temperatures $\gtrsim 100 \text{ K}$ (see §6.1).

5.4.19. NGC 7538 IRS 9

Deeply embedded cold IR source $\sim 50''$ south of IRS 1 that is associated with a large reflection nebula (Werner et al. 1979). The radial velocity of the IRS 9 cloud core from H^{13}CN , CS, and H_2CO data is about -57 km s^{-1} (Sandell et al. 2005; van der Tak et al.

2000), consistent with our observations. Single-dish JCMT H_2CO ($3_{22}\text{--}2_{21}$ and $3_{21}\text{--}2_{20}$, 218 GHz) spectra suggest a gas temperature of $\geq 60 \text{ K}$ (Sandell et al. 2005), while HCO^+ , H^{13}CO^+ , and ^{13}CO observations suggest a lower temperature of $\sim 30 \text{ K}$ (Hasegawa & Mitchell 1995; Mitchell et al. 1990). Mitchell et al. (1990) also detect the presence of warm gas (180 K) and suggest that the density of this material is $> 10^6 \text{ cm}^{-3}$.

6. LIMITATIONS OF $\text{H}_2\text{CO } J = 3/J = 4$ K -DOUBLET DENSITOMETRY

Our study is concerned primarily with the application of a previously unused densitometry technique and, as such, well-studied objects were chosen to assess the method's performance. This discussion is focused on limitations to the technique that require elaboration. These effects may also help explain the problem of the anomalously low transition ratios $[\int T_{mb}(3_{12} - 3_{13})d\nu / \int T_{mb}(4_{13} - 4_{14})d\nu]$ that precluded LVG modeling in a few sources (see Table 4).

TABLE 7
TEMPERATURE DEPENDENCE OF LVG DENSITY DERIVATION

T_K (K)	$\log[n(\text{H}_2)]^a$ (cm^{-3})	% Difference Over T_K Range
30–50	7.72–6.71	923
50–100	6.71–6.12	290
100–150	6.12–5.91	59.2
150–200	5.91–5.81	26.2
200–250	5.81–5.75	15.0
250–300	5.75–5.69	15.0

^a Calculated for test case NGC 7538 IRS 1.

6.1. LVG Model Dependence on Kinetic Temperature

The LVG model for the $3_{12}\text{--}3_{13}$ and $4_{13}\text{--}4_{14}$ transitions is somewhat dependent on kinetic temperature (T_K). As previously mentioned in §5.1, this meant that a careful selection of appropriate kinetic temperatures from previous studies was necessary. Wherever possible, temperatures derived from H_2CO measurements were used to ensure coupling to the gas traced by our observations. Estimates taken from analyses of other dense gas tracers such as NH_3 or CH_3CN are otherwise preferable. That said, any time a temperature derived from measurements of disparate molecules (or even H_2CO measurements of significantly different excitation requirements) is adopted, the question of whether or not this estimate can be associated with the gas sampled by our beam must be raised. In at least one case (NGC 7538 IRS 1, §5.4.18) there appears to be a distinct possibility that the temperature we adopted may not be wholly appropriate for the material traced by our observations.

In Table 4, we elected to include the spatial densities derived for a range of kinetic temperatures based on the error estimates in our assumed values. This is because the temperature dependence of our H_2CO LVG models is not linear and itself depends on the range of physical parameters being studied. Table 7 provides a summation of this dependence by dividing the range of kinetic temperatures found in our sample into 6 groups. The

test case of NGC 7538 IRS 1 was chosen for its moderate transition ratio (R_i) of 1.20. From the table it is clear that the dependence on T_K decreases with an increase in the assumed kinetic temperature. In the most volatile range (30–50 K) the measured density can fluctuate by upwards of an order of magnitude between the extremes. Fortunately, very few of our sources fall in this range. At high temperatures ($\gtrsim 200$ K) the dependence on T_K is fairly constant. In this regime, uncertainties in the derived density due to errors in the adopted kinetic temperature are generally below the uncertainty imposed by the collisional excitation rates between H_2CO and H_2 (20%; see §5.1).

Figure 5 provides a graphical representation of the H_2CO LVG model’s dependence on T_K with plots identical to that of Figure 4 for a source of high and low kinetic temperature. Note how at high temperatures (upper panel), the transition ratio and brightness temperature contours approach orthogonality. In effect, this means that as the kinetic temperature varies and the locations of the curves change with respect to each other, the intersection point between them is moved by smaller amounts at higher temperatures. For $T_K \gtrsim 200$ K, the brightness temperature (solid-line) contours become roughly horizontal and the solution point is therefore only affected by the lateral motion of the transition ratio contours. This is why a variation in T_K from 200–250 K produces the same variation in spatial density as 250–300 K (see Table 7).

It should also be noted that, depending on the observed $J = 3/J = 4$ integrated intensity (line) ratio, the kinetic temperature assumption can be the deciding factor in whether or not the LVG model can successfully match an observation. At high temperatures, the higher excitation $J = 4$ transition can start to enjoy a greater relative population than the $J = 3$, and $R_i < 1$ can reasonably be expected. In Table 4 there are 3 sources, L1551 IRS 5, Orion-S, and DR 21(OH)-MM1, with transition ratios on order ~ 0.9 . This was not a problem for the assumed temperature, but at the lower temperature limit, the density is indicated to be $> 10^8$ (column 5). This is to say that the LVG prediction for the density is unbound at such low temperatures. In terms of Figure 5, for kinetic temperatures below a given value, the transition ratio (color) and brightness temperature (solid-line) contours no longer intersect (as in Cep A East from Figure 4).

Given this discussion and the uncertainties typical in estimates of kinetic temperature, we suggest that H_2CO $3_{12}\text{--}3_{13}/4_{13}\text{--}4_{14}$ densitometry is best suited to objects with $T_K \gtrsim 100$ K. We have demonstrated that this technique is also viable at lower kinetic temperatures but with the caveat that its results become increasingly sensitive to uncertainties in the assumed value of T_K . The reason for this effect can likely be attributed to the relative excitation requirements of the $J = 3$ and 4 transitions, which are discussed in the following section.

6.2. H_2CO $3_{12}\text{--}3_{13}$ and $4_{13}\text{--}4_{14}$ Relative Excitation Requirements

In addition to the kinetic temperature of an object, it is important to consider the relative excitation requirements for each transition. Being of lower excitation, the $3_{12}\text{--}3_{13}$ transition can be excited by temperatures and densities lower than that required by the $4_{13}\text{--}4_{14}$ transi-

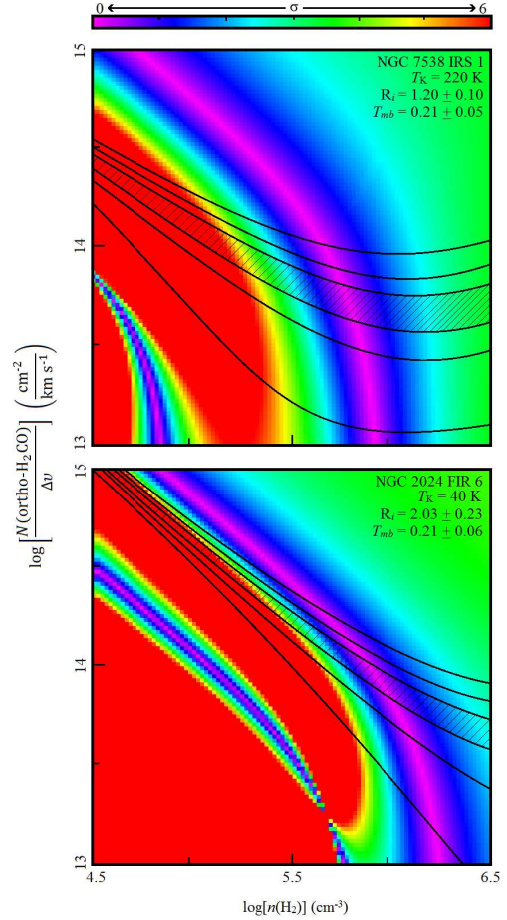


FIG. 5.— Comparison of model results for sources of high (upper panel) and low (lower panel) kinetic temperature. Contours and parameters are as in Fig. 4. Note how at high T_K , contours approach orthogonality, resulting in less variation in the solution point due to changes in T_K (alternatively, less dependence on T_K).

tion. This means that the $J = 3$ transition is predictably observed to be more intense than the $J = 4$ in the general case. What complicates the matter is that the two transitions are affected differently by the collisional pumping mechanism described in §2. In effect, this means that the $4_{13}\text{--}4_{14}$ transition falls into absorption at a slightly higher spatial density than the $3_{12}\text{--}3_{13}$. Therefore a small band of parameter space, briefly described in §5.2, exists for which the $J = 4$ transition is in absorption while the $J = 3$ is in emission.

It may be counterintuitive, then, that only one absorption component was detected in the $4_{13}\text{--}4_{14}$ transition while 9 were observed in the $3_{12}\text{--}3_{13}$. This is explained by two effects. The first is that the system temperatures for the $J = 4$ (Q-band) observations were substantially higher than the $J = 3$ (Ka-band), resulting in much noisier $4_{13}\text{--}4_{14}$ spectra. Looking at the spectra in Figure 1, the majority of absorption components detected in the $3_{12}\text{--}3_{13}$ transition are below the noise of the $4_{13}\text{--}4_{14}$ spectra. The second, and perhaps more significant, effect is that the $J = 3$ beam is substantially larger than that of the $J = 4$, meaning that the material being sampled is a bit different for each transition. This topic is addressed in §6.3.

Figure 6 displays the excitation temperatures of the

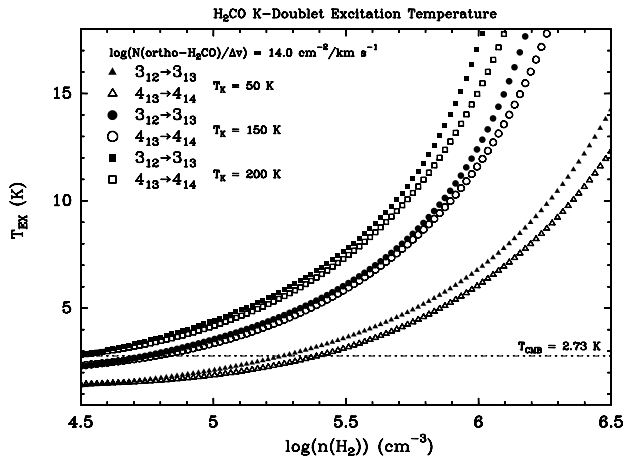


FIG. 6.— H_2CO $J = 3$ and 4 K -doublet excitation temperatures as a function of molecular hydrogen density for an ortho- H_2CO column density per velocity gradient roughly equivalent to the average value observed in our sample. Note that the possibility for absorption is much smaller at high kinetic temperatures than it is for low. Values predicted via LVG modeling.

$J = 3$ and 4 transitions as a function of spatial density for an ortho- H_2CO column density roughly equivalent to the average of that observed in our sample. From this, we can see the effect of the collisional pumping mechanism described in §2, which cools the excitation temperatures of the $J \leq 5$ K -doublet transitions to lower than 2.73 K for a given set of physical conditions, allowing them to absorb radiation from the cosmic microwave background. Curves for kinetic temperatures of 50, 150, and 200 K are shown. Note how at high kinetic temperatures, the excitation temperatures for both transitions match more closely and only barely fall below the 2.73 K level. This means that at high kinetic temperatures, the possibility of observing absorption is small and the difference between the excitation requirements of each transition is of less consequence. This is likely the reason why the $3_{12}-3_{13}/4_{13}-4_{14}$ densitometry technique is best suited for temperatures $\gtrsim 100$ K.

6.3. The Effects of Spatial Extent

Because the beam sizes differ by $(\theta_b(29\text{ GHz}) - \theta_b(48\text{ GHz}))/\theta_b(48\text{ GHz}) = 63\%$, it is important to consider the distribution of dense gas in each object as the larger beam size observations ($J = 3$) may be sampling extended structure that biases the resulting line ($J = 3/J = 4$ integrated intensity) ratio. In similar studies using the $1_{10}-1_{11}$ and $2_{11}-2_{12}$ K -doublets, the beam sizes of both observations ($153''$ and $51''$, respectively, for the GBT) can generally be considered much larger than the dense gas distribution and it is safe to assume that all relevant emission is sampled. One advantage of the $3_{12}-3_{13}$ and $4_{13}-4_{14}$ transitions is that their smaller beam sizes ($26''$ and $16''$, respectively, for the GBT) allow for higher resolution and heightened sensitivity to the spatially compact regions in which stars are known to form. However, these beam sizes also approach the spatial extent of molecular cores and it is therefore prudent to consider potential differences in the material being sampled by each observation.

Unfortunately, no mapping measurements of the H_2CO $J = 3$ and 4 K -doublet transitions exist. We experimented with assuming spatial extents derived from other

dense gas tracers in the literature but ultimately decided that inconsistencies in the frequency, chosen tracer, excitation conditions, and spatial resolution precluded truly appropriate spatial extent estimates for our purpose. Instead, source sizes equal to the smaller beam size ($16''$) were assumed and the $J = 3$ observations were scaled for beam dilution (see §3). We find this agreeable because $16''$ is a reasonable average value for estimates of the dense gas distribution in most of our sources, but this is surely not appropriate for each application.

It is also possible for an object's dense gas distribution to be significantly smaller than $16''$, in which case the $J = 4$ observation is also subject to beam dilution. To examine this effect, consider the case of L1551 IRS 5, for which high-resolution imaging of CS suggests the dense gas to be distributed over $\sim 7''$ (Takakuwa et al. 2004). Applying the beam dilution correction described in §3 to this case has the effect of boosting the intensity of both transitions, but comparatively more for the $J = 3$ observation, resulting in an increased transition ratio $[\int T_{mb}(3_{12}-3_{13})d\nu/\int T_{mb}(4_{13}-4_{14})d\nu]$. The subsequent LVG approximation to the density ($10^{5.95}\text{ cm}^{-3}$) is nearly an order of magnitude lower than that of the $16''$ assumption ($10^{6.87}\text{ cm}^{-3}$). This decrease is mainly due to an increased optical depth in the modelled transitions.

In several sources, the transition ratio was anomalously low (see Table 4), meaning that the $J = 3$ transition was observed to be unexpectedly less intense than the $J = 4$. This is possible at temperatures and densities high enough to populate the higher excitation transition significantly more than the lower, but these conditions are not met by the sources in question. One possible explanation for this effect is that the $J = 3$ transition is being subjected to absorption that is not reflected in the line profile other than to lower its intensity. The LVG model assumes a uniform spatial density, which proves to be a reasonable approximation but ignores a density gradient that likely exists in molecular cores, with the outer regions being comparatively less dense than the inner. It is possible that the larger $J = 3$ beam is sampling the comparatively cool, diffuse material enveloping a molecular core which has resulted in some self absorption. Indeed, in a few sources (e.g. NGC 1333 IRAS 4B and Orion-S, §5.4.4 and §5.4.7, respectively), H_2CO absorption has been detected in the $J = 2$ or 1 K -doublet transitions over the velocity range in question. Mapping studies are required to disentangle the varying density structure in many of the sources in our sample.

7. CONCLUSION

Using observations of the $3_{12}-3_{13}$ and $4_{13}-4_{14}$ transitions of H_2CO , we have successfully constrained the spatial densities of a sample of galactic star-forming regions. Both transitions were observed toward 18 sources with relative ease, requiring an average of 17 min of integration time and resulting in only 3 nondetections in the $J = 4$ transition. Accurate measurements of the spatial density $[n(\text{H}_2)]$ were made for 13 objects and useful limits were placed on the remainder using a combination of Large Velocity Gradient (LVG) and Local Thermodynamic Equilibrium (LTE) analyses. Molecular hydrogen densities in the range of $10^{5.5}-10^{6.5}\text{ cm}^{-3}$ and ortho-formaldehyde column densities per unit line width between $10^{13.5}$ and $10^{14.5}\text{ cm}^{-2}(\text{km s}^{-1})^{-1}$ are found for

most sources, in general agreement with previous measurements.

Detailed analyses of the advantages and limitations to this densitometry technique have also been provided. H_2CO $3_{12}\text{--}3_{13}/4_{13}\text{--}4_{14}$ densitometry proves to be best suited to objects with $T_K \gtrsim 100$ K, above which the H_2CO LVG models become relatively independent of kinetic temperature. Compared with the similarly utilized $1_{10}\text{--}1_{11}$ and $2_{11}\text{--}2_{12}$ transitions, the $J = 3$ and 4 K -doublets provide higher spatial resolution and sensitivity to hot, dense material, which makes them more efficient probes of spatial density in molecular cores. However, beam widths comparable to the anticipated source sizes make source structure considerations important. Since mapping measurements have yet to be conducted for these transitions, the correlation between the spatial extent traced by the $J = 3$ and 4 K -doublets and that of other dense gas tracers is uncertain, making spatial assumptions based on past measurements problematic.

This work serves as a successful proof-of-concept for the H_2CO $J = 3/J = 4$ K -doublet densitometry technique, adding a useful new diagnostic to the study of dense molecular environments.

The Green Bank Telescope (GBT) staff was characteristically helpful and contributed significantly to the success of our observing program. The authors also thank the referee for several comments that greatly enhanced this work. P. I. M. would like to thank Harold Butner and the NRAO REU students of 2009 for their continued support. Funding for this project was provided by the NSF through the NRAO REU Program (award No. 0755390) and by NRAO through an undergraduate internship.

Facilities: GBT

REFERENCES

- Anthony-Twarog, B. J. 1982, *AJ*, 87, 1213
 Araya, E., Hofner, P., Olmi, L., Kurtz, S., & Linz, H. 2006, *ApJ*, 132, 1851
 Barsony, M., Ward-Thompson, D., André, P., & O’Linger, J., *ApJ*, 1998, 509, 733
 Bastien, P., Batrla, W., Henkel, C., Pauls, T., Walmsley, C. M., & Wilson, T. L. 1985, *A&A*, 146, 86
 Batrla, W., Wilson, T. L., Ruf, K., & Bastien, P. 1983, *A&A*, 128, 279
 Baudry, A., & Menten, K. M. 1995, *A&A*, 298, 905
 Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987, *ApJ*, 315, 621
 Blake, G. A., Sandell, G., van Dishoeck, E. F., Groesbeck, T. D., Mundy, L. G., & Aspin, C. 1995, *ApJ*, 441, 689
 Brogan, C. L., Chandler, C. J., Hunter, T. R., Shirley, Y. L., & Sarma, A. P. 2007, *ApJ*, 660, L133
 Butner, H. M., Evans, N. J., II, Lester, D. F., Levreault, R. M., & Strom, S. E. 1991, *ApJ*, 376, 636
 Campbell, M. F., Lester, D. F., Harvey, P. M., & Joy M. 1989, *ApJ*, 345, 298
 Chen, H., Tokunaga, A. T., Strom, K. M., & Hodapp, K. -W. 1993, *ApJ*, 407, 639
 Chen, H., Ohashi, N., & Umemoto, T. 1996, *A&A*, 112, 717
 Churchwell, E., Walmsley, C. M., & Wood, D. O. S. 1992, *A&A*, 253, 541
 Codella, C., Bachiller, R., Benedettini, M., Caselli, P., Viti, S., & Wakelam, V. 2005, *MNRAS*, 361, 244
 Cohen, M., Harvey, P. M., Wilking, B. A., & Schwartz, R. D. 1984, *ApJ*, 278, 671
 Comito, C., Schilke, P., Endesfelder, U., Jiménez-Serra I., & Martín-Pintado, J. 2007, *A&A*, 469, 207
 Crutcher, R. M., Henkel, C., Wilson, T. L., Johnston, K. J., & Bieging, J. H. 1986, *ApJ*, 307, 302
 Cyganowski, C. J., Brogan, C. L., & Hunter, T. R. 2007, *AJ*, 134, 346
 Dickel, H. R., & Goss, W. M. 1987, *A&A*, 185, 271
 Dickel, H. R., Goss, W. M., & Condon, G. R. 1996, *ApJ*, 460, 716
 Di Francesco, J., Myers, P. C., Wilner, D. J., Ohashi, N., & Mardones, D. 2001, *ApJ*, 562, 770
 Downes, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, *A&AS*, 40, 379
 Dreher, J. W., & Welch, W. J. 1981, *ApJ*, 245, 857
 Eiroa, C., Djupvik, A. A., & Casali, M. M. 2008, in *The Southern Sky ASP Monograph Publications*, ed. B. Reipurth, *Handbook of Star Forming Regions*, II, 5, 693
 Emprechtinger, M., Wiedner, M. C., Simon, R., Wiechin, G., Volgenau, N. H., Bielau, F., Graf, U. U., Güsten, R., Honingh, C. E., Jacobs, K., Rabanus, D., Stutzki, J., & Wyrowski, F. 2009, *A&A*, 496, 731
 Evans, N. J., II, Morris, G., Sato, T., & Zuckerman, B. 1975, *ApJ*, 196, 433
 Fuller, G. A., Ladd, E. F., Padman, R., Myers, P. C., & Adams, F. C. 1995, *ApJ*, 454, 862
 Garay, G., Ramírez, S., Rodríguez, L. F., Curiel, S., & Torrelles, J. M. 1996, *ApJ*, 459, 193
 Garrison, B. J., Lester, W. A., Jr., Miller, W. H., & Green, S. 1975, *ApJ*, 200, L175
 Gaume, R. A., Johnston, K. J., & Wilson, T. L. 1993, *ApJ*, 417, 645
 Genzel, R. & Stutzki, J. 1989, *ARA&A*, 27, 41
 Green, S. 1991, *ApJS*, 76, 979
 Guilloteau, S., Stier, M. T., & Downes, D. 1983, *A&A*, 126, 10
 Hasegawa, T., & Mitchell, G. F. 1995, *ApJ*, 441, 665
 Heaton, B. D., Little, L. T., & Bishop, I. S. 1989, *A&A*, 213, 148
 Helmich, F. P., Jansen D. J., de Graauw, Th., Groesbeck, T. D., & van Dishoeck, E. F. 1994, *A&A*, 283, 626
 Henkel, C., Walmsley, C. M., & Wilson, T. L. 1980, *A&A*, 82, 41
 Henkel, C., Wilson, T. L., & Bieging, J. 1982, *A&A*, 109, 344
 Heyer, M. H., Snell, R. L., Morgan, J., & Schloerb, F. P. 1989, *ApJ*, 346, 220
 Hirota, T., Bushimata, T., Choi, Y. K., et al. 2008, *PASJ*, 60, 37
 Hodapp, K. -W., & Deane, J. 1993, *ApJS*, 88, 119
 Hoffman, I. M., Goss, W. M., Palmer, P., & Richards, A. M. S. 2003, *ApJ*, 598, 1061
 Hurt, R. L., Barsony, M., & Wootten, A. 1996, *ApJ*, 456, 686
 Johnston, K. J., Palmer, P., Wilson, T. L., & Bieging, J. H. 1983, *ApJ*, 271, L89
 Kenyon, S. J., Dobrzycka, D., & Hartmann, L. 1994, *AJ*, 108, 1872
 Kim, M. K., Hirota, T., Honma, M., et al. 2008, *PASJ*, 60, 991
 Kitamura, Y., Kawabe, R., & Ishiguro, M. 1992, *PASJ*, 44, 407
 Kuchar, T. A., & Bania, T. M. 1994, *ApJ*, 436, 117
 Looney, L. W. 1998, Ph.D. Thesis, Univ. Maryland
 Looney, L. W., Mundy, L. G., & Welch, W. J. 2000, *ApJ*, 529, 477
 Lugo, J., Lizano, S., & Garay, G. 2004, *ApJ*, 614, 807
 Mangum, J. G., Wootten, A., Wadiak, E. J., & Loren, R. B. 1990, *ApJ*, 348, 542
 Mangum, J. G., Wootten, A., & Mundy, L. G. 1991, *ApJ*, 378, 576
 Mangum, J. G., Wootten, A., & Mundy, L. G. 1992, *ApJ*, 388, 467
 Mangum, J. G., Wootten, A., & Plambeck, R. L. 1993, *ApJ*, 409, 282
 Mangum, J. G., & Wootten, A. 1993, *ApJS*, 89, 123
 Mangum, J. G., Wootten, A., & Barsony, M. 1999, *ApJ*, 526, 845
 Mangum, J. G., Darling, J., Menten, K. M., & Henkel, C. 2008, *ApJ*, 673, 832
 Maret, S., Ceccarelli, C., Caux, E., Tielens, A. G. G. M., Jørgenson, J. K., van Dishoeck, E., Bacmann, A., Castets, A., Lefloch, B., Loinard, L., Parise, B., & Schöier, F. L. 2004, *A&A*, 416, 577
 Martin, A. H. M. 1972, *MNRAS*, 157, 31
 Martin, A. H. M. 1973, *MNRAS*, 163, 141

- Mauersberger, R., Wilson, T. L., & Henkel C. 1988, A&A, 201, 123
- McMullin, J. P., Mundy, L. G., & Blake, G. A. 1993, ApJ, 405, 599
- McMullin, J. P., Mundy, L. G., & Blake, G. A. 1994, ApJ, 437, 305
- McMullin, J. P., Mundy, L. G., Blake, G. A., Wilking, B. A., Mangum, J. G., & Latter, W. B. 2000, ApJ, 536, 845
- Mezger, P. G., Zylka, R., & Wink, J. E. 1990, ApJ, 228, 95
- Mezger, P. G., Sievers, A. W., Haslam, C. G. T., Kreysa, E., Lemke, R., Mauersberger, R., & Wilson, T. L. 1992, A&A, 256, 631
- Mitchell, G. F., Maillard, J. -P., Allen, M., Beer, R., & Belcourt, K. 1990, ApJ, 363, 554
- Mookerjee, B., Casper, E., Mundy, L. G., & Looney, L. W. 2007, ApJ, 659, 447
- Moriarty-Schieven, G. H., Wannier, P. G., Mangum, J. G., Tamura M., & Olmsted, V. K. 1995, ApJ, 455, 190
- Moscadelli, L., Xu, Y., & Chen, X. 2010, ApJ, 716, 1356
- Myers, P. C., & Buxton, R. B. 1980, ApJ, 239, 515
- Nerf, R. B. Jr. 1975, J. Mol. Spec., 58, 451
- Odenwald, S. F., & Schwartz, P. R. 1993, ApJ, 405, 706
- Patel, N. A., Curiel, S., Sridharan, T. K., et al. 2005, Nature, 437, 109
- Pendleton, Y., Werner, M. W., Capps, R., & Lester, D. 1986, ApJ, 311, 360
- Persson, S. E., Geballe, T. R., Simon, T., Lonsdale, C. J., & Baas, F. 1981, ApJ, 251, L85
- Pratap, P., Batrla, W., & Snyder, L. E. 1989, ApJ, 341, 832
- Qiu, K., Zhang, Q., & Menten, K. M. 2011, ApJ, 728, 6
- Reid, M. J., Menten, K. M., Zheng, X. W., Brunthaler, A., Moscadelli, L., Xu, Y., Zhang, B., Sato, M., Honma, M., Hirota, T., Hachisuka, K., Choi, Y. K., Moellenbrock, G. A., & Bartkiewicz 2009, ApJ, 700, 137
- Remijan, A., Sutton, E. C., Snyder, L. E., Friedel, D. N., Liu, S. -Y., & Pei, C. -C. 2004, ApJ, 606, 917
- Roberts, H., Fuller, G. A., Millar, T. J., Hatchell, J., & Buckle, J. V. 2002, A&A, 381, 1026
- Roberts, H., & Millar, T. J. 2007, A&A, 471, 849
- Rots, A. H., Dickel, H. R., Forster, J. R., & Goss, W. M. 1981, 245, L15
- Rygl, K. L. J., Brunthaler, A., Reid, M. J., Menten, K. M., van Langevelde, H. J., & Xu, Y. 2010, A&A, 511, id.A2
- Sandell, G., Aspin, C., Duncan, W. D., Russell, A. P. G., & Robson, E. I. 1991, ApJ, 376, L17
- Sandell, G., Goss, W. M., & Wright, M. 2005, ApJ, 621, 839
- Sato, M., Reid, M. J., Brunthaler, A., & Menton, K. M. 2010, ApJ, 720, 1055
- Sobolev, V. V. 1960, *Moving Envelopes of Stars* (Cambridge: Harvard Univ. Press)
- Stanke, T., & Williams, J. P. 2007, ApJ, 133, 1307
- Strom, K. M., Margulis, M., & Strom, S. E. 1989, ApJ, 346, L33
- Takakuwa, S., Ohashi, N., Ho, P. T. P., Qi, C., Wilner, D. J., Zhang, Q., Bourke, T. L., Hirano, N., Choi, M., & Yang, J. 2004, ApJ, 616, L15
- Takano, T., Fukui, Y., Ogawa, H., Takaba, H., Kawabe, R., Fujimoto, Y., Sugitani, K., & Fujimoto, M. 1984, ApJ, 282, L69
- Tauber, J. A., Goldsmith, P. F., & Snell, R. L. 1988, ApJ, 325, 846
- Terebey, S., & Padgett, D. L. 1997, IAUS, 182, 507T
- Torrelles, J. M., Gómez, J. F., Rodríguez, L. F., Curiel, S., Ho, P. T. P. & Garay, G. 1996, ApJ, 457, L107
- Troscompt, N., Faure, A., Wiesenfeld, L., Ceccarelli, C., & Valiron, P. 2009, A&A, 493, 687
- Turner, B. E., Richard, L. J., & Xu, L. 1989, ApJ, 344, 292
- van Buren, D., Mac Low, M. -M., Wood, D. O. S., & Churchwell, E. 1990, ApJ, 353, 570
- van der Tak, F. F. S., van Dishoeck, E. F., Evans, N. J., II, & Blake, G. A. 2000, ApJ, 537, 283
- Volgenau, N. H., Mundy, L. G., Looney, L. W., & Welch, W. J. 2006, ApJ, 651, 301
- Walker, C. K., Adams, F. C., & Lada, C. J. 1990, ApJ, 349, 515
- Watanabe, T., & Mitchell, G. F. 2008, AJ, 136, 1947
- Watt, S., & Mundy, L. G. 1999, ApJS, 125, 143
- Welch, W. J. 1970, BAAS, 2Q, 355W
- Werner, M. W., Becklin, E. E., Gatley, I., Matthews, K., Neugebauer, G., & Wynn-Williams, C. G. 1979, MNRAS, 188, 463
- Wink, J. E., Duvert, G., Guilloteau, S., Güsten, R., Walmsley, C. M., & Wilson, T. L. 1994, A&A, 281, 505
- Wilson, T. L., Walmsley, C. M., Henkel, C., Pauls, T., & Mattes H. 1980, A&A, 91, 36
- Wilson, T. L., Walmsley, C. M., Batrla, W., & Mauersberger, R. 1983, A&A, 127, L19
- Wolf-Chase, G. A., Barsony, M., Wootten, A., Ward-Thompson, D., Lowrance, P. J., Kastner, J. H., & McMullin, J. P. 1998, ApJ, 501, L193
- Wood, D. O. S., & Churchwell, E. 1989, ApJS, 69, 831
- Wynn-Williams, C. G., Becklin, E. E., & Neugebauer, G. 1972, MNRAS, 160, 1
- Zhang, Q., & Ho, P. T. P. 1997, ApJ, 488, 241
- Zhou, S., Evans, N. J., II, Güsten, R., Mundy, L. G., & Kutner, M. L. 1991, ApJ, 372, 518
- Zylka, R., Güsten, R., Henkel, C., & Batrla, W. 1992, A&A, 96, 525